Angle-dependent properties of MorphoColor™ solar collectors: Color stability, IAM, yield

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Abstract

MorphoColor™ coatings were developed for application in solar thermal flat-plate collectors and their marketability was ensured in the project, "Color Collector - Concepts for Architecturally Adapted Collectors for Existing and New Buildings", which is funded by the German Federal Ministry of Economic Affairs and Climate Action (BMWK), funding code 03ETW007A. The project is coordinated by Fraunhofer ISE, which is co-operating with Interpane E&B GmbH, Siko GmbH, THIEME GmbH & Co. KG and Fuchs Design GmbH as project partners.

The influence of the color on the annual yield was minimized. The design possibilities shown in this article represent only a small portion of all possibilities. The first applications of MorphoColor™ collectors in Jenbach, Austria and Freiburg, Germany are currently being implemented and are being monitored by Fraunhofer ISE.

Keywords: Building-integrated solar thermal, high-transmittance colored coating, design, performance, simulation, monitoring

1. Introduction to MorphoColor™ technology

The German government is aiming for a climate-neutral building stock by 2045. Architecturally integrated roof and façade collectors can make a significant contribution to the transformation of the energy system. For these architecturally integrated solar thermal applications, the design of the solar collectors plays a decisive role. With the MorphoColor™ technology, we present an approach that makes aesthetically valuable solar collectors with high efficiency feasible.

The starting point for the development was a phenomenon that can be observed in the morpho butterfly. Its is distinguished by the strong blue coloration of its wings, which is produced by a 3D surface structure with lamellae on a nanometer scale. Inspired by this, glass panes with MorphoColor™ coatings were developed for use as collector covers. The color impression is created by an interference layer system on a glass substrate with a microscopically structured surface. For a description of the basic function of the MorphoColor™ layers, please refer to (Bläsi et al. 2021). The first application in solar thermal collectors is described by Wessels et al. (Wessels et al. 2021, 2021).

The glass panes coated with MorphoColor™ offer very interesting properties for solar thermal collectors:

- High solar yield (> 90% of clear glass)
- Saturated colors
- Anti-glare design
- High angular stability of the color impression
- Absorber almost completely invisible behind colored layer
- Simple integration into collectors due to thermally pre-stressable coating

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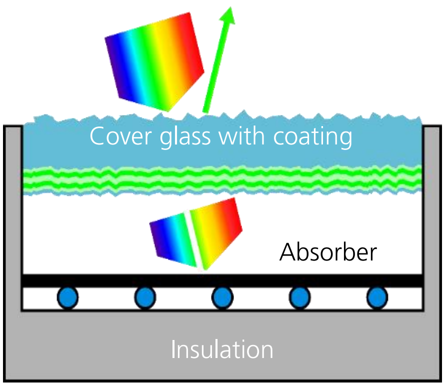

Fig. 1: Schematic illustration of a collector with a MorphoColor™ glass cover

2. Angle-dependent spectral evaluations in reflection

Angle-dependent reflectance measurements were carried out on MorphoColor™ coated, structured glasses by means of an Agilent Cary 5000 spectrometer and using the Universal Measurement Accessory (UMA). Both the angle of incidence and the angle of reflection can be varied within an azimuthal plane. Fig. 2 shows examples of reflectance spectra at different reflection angles θ_R for an angle of incidence of -30°. As can be seen in the schematic drawing in Fig. 2, all angles are defined relative to the normal to the glass sample. The spectra clearly show the narrow-band reflection peak characteristic of MorphoColor™ technology. The small spectral shift of the peak causes the colored appearance to remain very stable for different viewing angles.

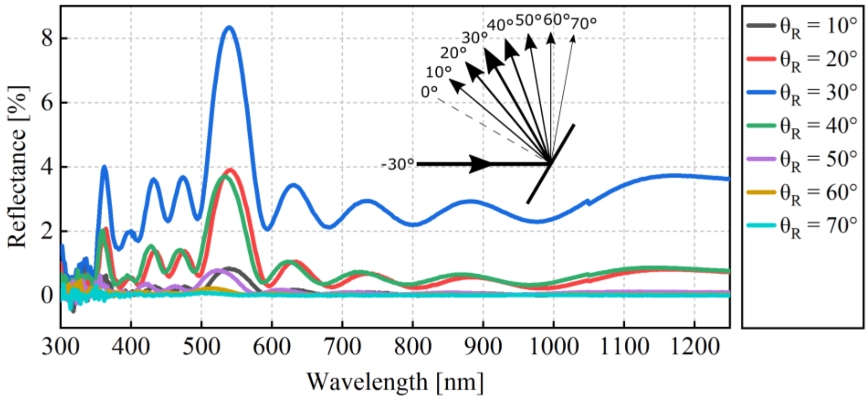

Fig. 2: Angle-dependent spectral data of a MorphoColor™ coated glass cover that is structured on one surface. The layer stack is located on the structured glass side and is designed so that the narrow reflection peak occurs at approx. 540 nm and thus looks green in reflection.

3. Color measurements with luminance camera under outdoor conditions

To visualize the appearance of MorphoColor™ solar collectors in real applications with complex environmental conditions, a demonstration collector was measured outdoors using a calibrated LMK color camera from the manufacturer, TechnoTeam. As also shown in the schematic of Fig. 1, the coated structured side of the glass cover is oriented towards the inside of the collector. The outside of the glass is not textured. Fig. 3 shows the resulting colors from different viewing angles in front of the west-facing collector. Photographs were taken both when the sky was clear (clear sky) and when it was overcast (overcast). In both cases, the sun was in the southwest. Comparing the colors under the different conditions shows clear differences. In the case of the clear sky, the direct reflection in the northwest results in significantly brighter colors than in the southwest, where the observer has the sun behind him. In the case of overcast skies, the colors appear much more homogeneous in terms of brightness due to the diffuse illumination. Looking not at the brightness but at the color tone, both sets of environmental conditions show very good angular stability. The color remains green and it is only at very large viewing angles that a tendency to shift towards gray tones becomes visible.

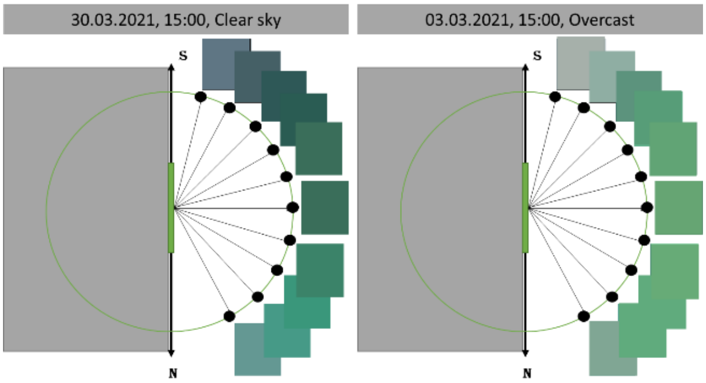

Fig. 3: Color measurements with a luminance camera under outdoor conditions. The MorphoColor™ solar collector sample was located vertically on a west-facing façade. The camera was located along the perimeter of a horizontal half-circle centered at the center of the sample.

Using a synchronized spectral weather station, both the sky and the direct irradiation of the sun were monitored in terms of their intensity and spectrum during the measurements. The combination of these data with the color data can be used in further work to calibrate and validate material models. These could be used to create a visualization tool.

4. Solar collector performance evaluation

With the aim of quantifying the performance and yield reduction of the MorphoColor™ solar collectors compared to a standard flat-plate collector (reference), the performance was characterized according to EN ISO 9806:2018, as well as the gross annual yield being simulated using ScenoCalc for different locations and collector mounting angles.

5. Efficiency curves of MorphoColor™ solar collectors

The efficiency curve of a reference collector with clear, uncoated glass was determined using the solar simulator of the TestLab Solar Thermal Systems at Fraunhofer ISE. The clear, uncoated glass cover was then replaced with MorphoColor™ coated and structured glass in the colors, blue, green, red, gold and grey and the conversion factor η_0 was determined in each case. To exclude influences on the determination of the conversion factor, the test stand configuration remained unchanged. The efficiency curves determined are shown in Fig. 4, normalized to the reference collector. The comparison of the characteristic curves shows that for the colors blue, green, and red, the reduction of the collector efficiency is in the range of 10 percentage points. This was one of the project goals and the result is consistent with the optical characterization of the MorphoColor™ glass panes.

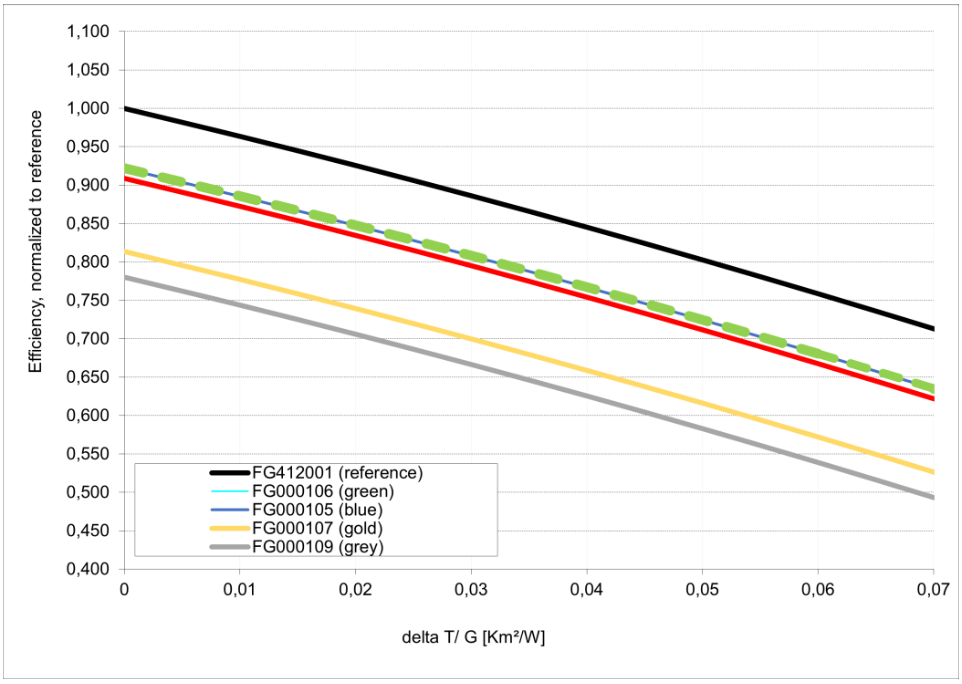

Fig. 4: Efficiency curves of the MorphoColor™ solar collectors, normalized to the reference collector.

6. Angle-dependent solar transmittance curves of MorphoColor™ glasses

The direct-hemispherical solar transmittance (Tdir-hem_sol) of MorphoColor™ glass panes in the five colors mentioned above and the glass cover of the reference collector were measured at different angles of incidence (cf. Fig. 5).

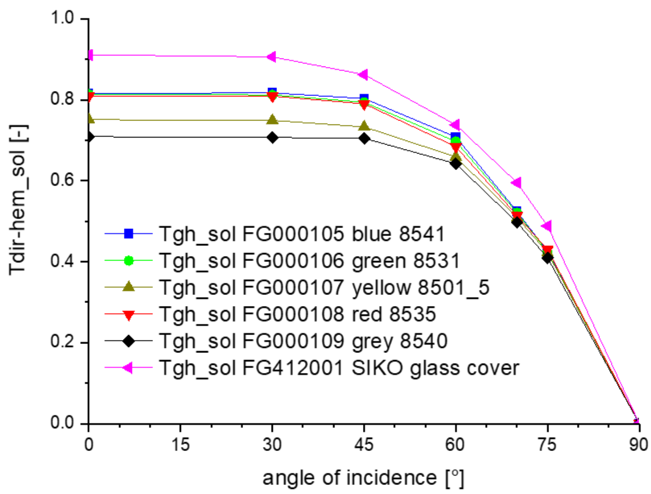

Fig. 5: Angular dependence of the direct-hemispherical solar transmittance (Tdir-hem_sol) for five MorphoColor™ glass covers in different colors and the original glass cover of a SIKO solar collector

Angle-dependent "calibration curves" for each MorphoColor™ glass pane were calculated from the ratio Tdir-hem_sol_Morpho to Tdir-hem_sol_reference. Multiplying these "calibration curves" by the IAM (Incidence Angle Modifier) curve for the reference collector leads to theoretical IAM curves for collectors covered with MorphoColor™ glass panes. The result shows no significant influence on the IAM result of collectors with MorphoColor™ glass panes for the Morpho coatings shown here. Compared to the reference, all coatings show increased IAM values. In particular, this can be observed in the range of incidence angles from 30° to 65°, which leads to the expectation of a positive influence on the result of the annual yield simulations (cf. Fig. 6).

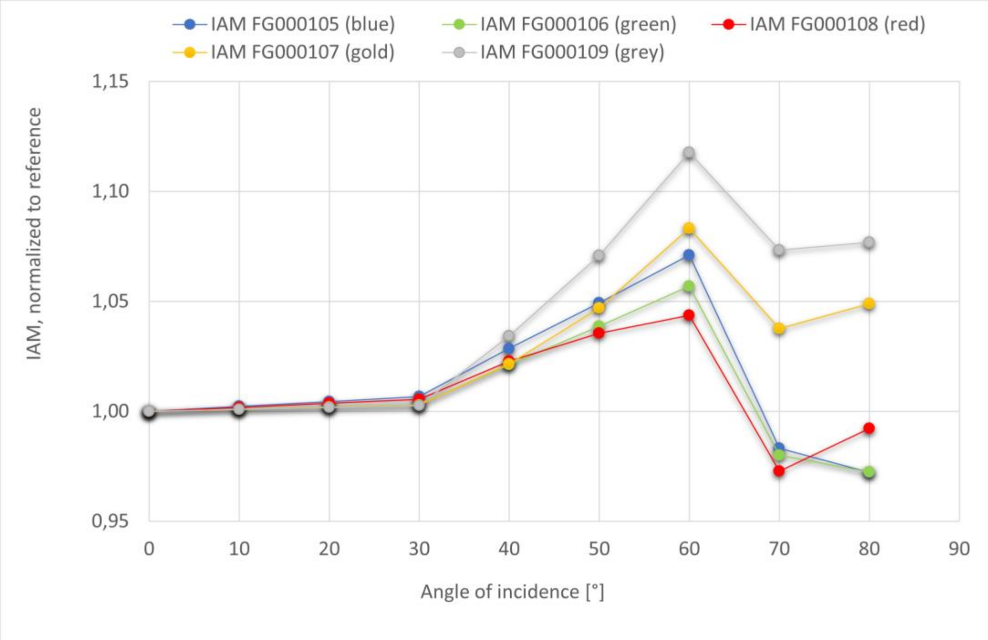

Fig. 6: Incidence Angle Modifier (IAM) of the MorphoColor™ solar collectors, normalized to the reference collector.

7. Acceptance of diffuse irradiance of MorphoColor™ solar collectors

The acceptance of diffuse irradiance K_d of the MorphoColor™ solar collectors and the reference collector were determined based on the theoretically determined IAM with the metrologically determined efficiency curves. The method used to determine the diffuse radiation acceptance is described in (EN ISO 9806:2018) and assumes an isotropic distribution of the diffuse irradiance over the sky hemisphere. The influence of the MorphoColor™ coating on the acceptance of diffuse irradiance of the MorphoColor™ solar collectors is shown in Fig. 7 normalized to the reference collector. The MorphoColor™ solar collectors show a slight increase in the acceptance of diffuse irradiance compared to the reference collector.

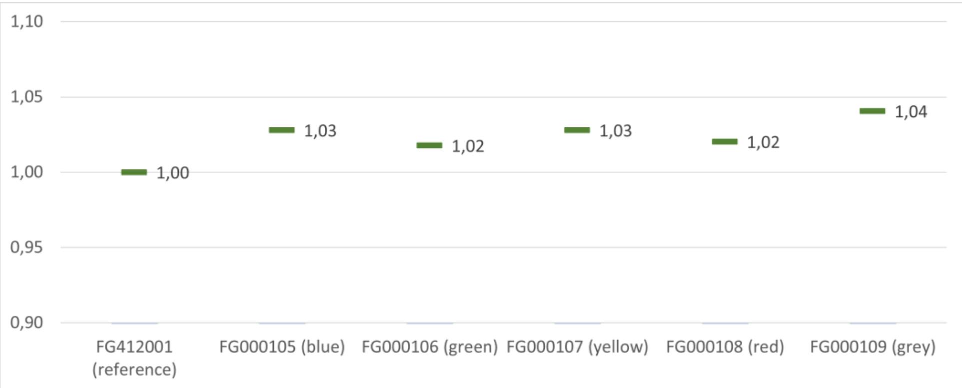

Fig. 7: Diffuse radiation acceptance of the MorphoColor™ solar collectors, normalized to the reference collector.

8. Gross annual yield of MorphoColor™ solar collectors

Based on the performance parameters of the indoor performance test, the theoretical IAM curves and the acceptance of diffuse irradiance, gross annual yield simulations were carried out using ScenoCalc. In addition to the tilt angles as a function of latitude, which were used in the context of collector certifications, all simulations were also carried out for vertical orientation of the collector. The simulations are based on constant collector operating temperature levels of 25°C, 50°C and 75°C. It is therefore assumed that the collector always operates at the same temperature level throughout the year. The mass flow rate is fixed at 72 kg/m²h. Also, no energy demand profiles are considered within the ScenoCalc simulation. The total energy produced over the course of the year is accumulated in the result to give the gross annual yield. ScenoCalc does not take capacitive effects into account. The result of ScenoCalc therefore does not show the expected performance of the collector in a real solar thermal system but is particularly suitable for comparing the annual yield of different collector variants based on the performance parameters and the IAM curve.

The gross annual yield of the MorphoColor™ solar collectors is shown for the locations, Würzburg, Stockholm, Davos and Athens, both for the standard tilt angle and for vertical orientation normalized to the reference collector (Figure 8 to Figure 11). The differences between the results for the individual locations are marginal. If the tilt angle of the collector corresponds to the latitude minus 10°, yield reductions result which are between 6 to 10 %-points at the fluid temperature of 25°C and 13 to 20 %-points at the fluid temperature of 75°C for the colors blue, green and red. The colors gold and grey show somewhat higher yield reductions due to the more complex layer structure. A similar picture emerges when the collector is set up vertically. Here, the yield reduction due to the use of the respective MorphoColor™ glass at the fluid temperature of 25°C is in a range of 5 to 10 %-points and at a fluid temperature of 75°C, is between 14 and 27-%- points. The reason for the greater influence when the collector is installed vertically is the reduced duration with high irradiatiance.

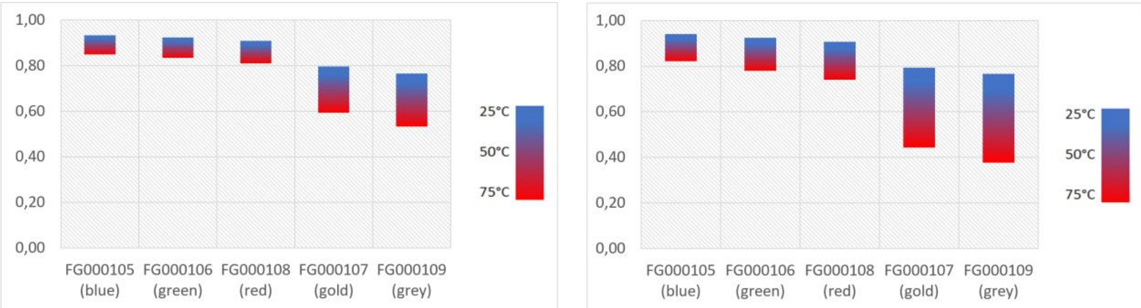

Fig. 8: Gross annual yield of MorphoColorTM solar collectors, normalized to the reference collector at the Würzburg site. Right, collector tilt angle = latitude -10°. Left, collector tilt angle = 90°.

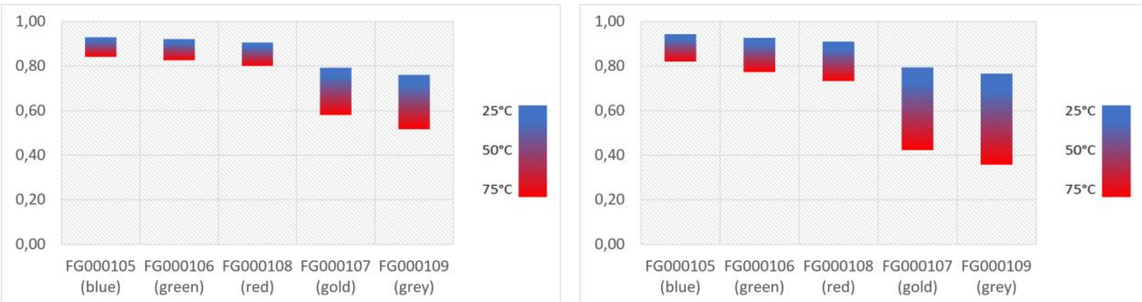

Fig. 9: Gross annual yield of MorphoColorTM solar collectors, normalized to the reference collector at the Stockholm site. Right, collector tilt angle = latitude -10°. Left, collector tilt angle = 90°.

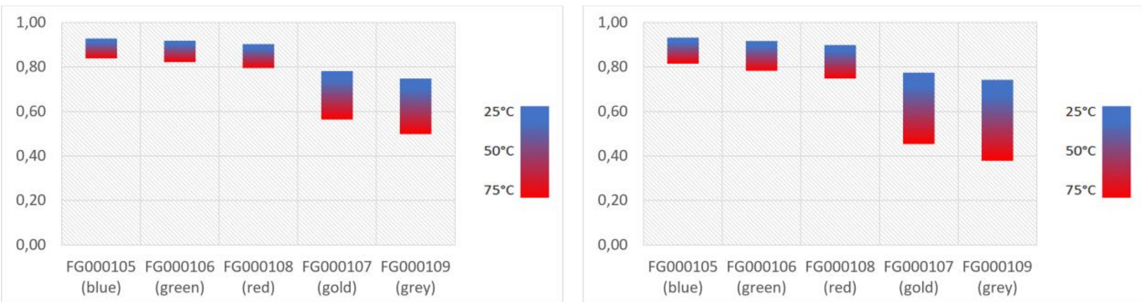

Fig. 10: Gross annual yield of the MorphoColorTM solar collectors, normalized to the reference collector at the Davos site. Right, collector tilt angle = latitude -10°. Left, collector tilt angle = 90°.

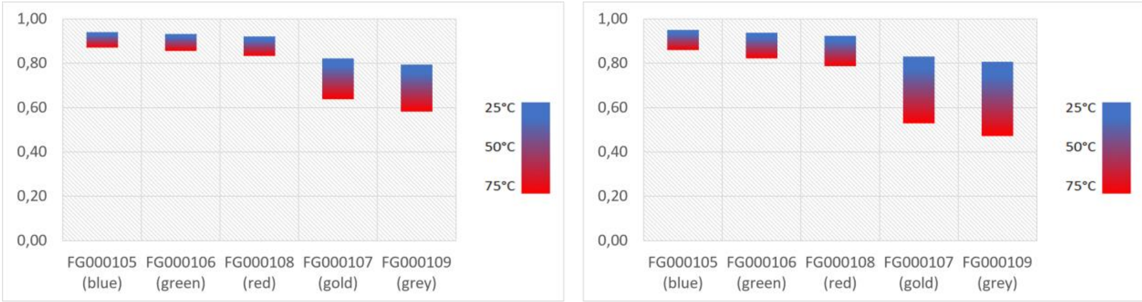

Fig. 11: Gross annual yield of the MorphoColorTM solar collectors, normalised to the reference collector at the Athens site. Right, collector tilt angle = latitude -10°. Left, collector tilt angle = 90°.

9. Marketability of MorphoColor™ solar collectors

To increase design freedom in the architectural integration of solar thermal energy as well as to ensure the marketability of MorphoColor™ glass, the goal was to achieve simple exchangeability of MorphoColor™ glass with the transparent covers of flat-plate collectors that already had a Solar KEYMARK certification.

The simplified process for the certification of collectors with MorphoColor™ glass is shown in Fig. 12. Note: The prerequisite is an existing Solar-Keymark certification of a flat-plate collector.

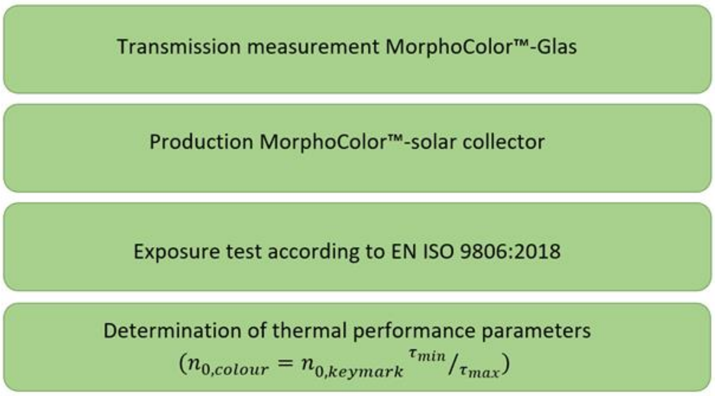

Fig. 12: Process flow for Solar Keymark certification when replacing the transparent cover of a certified flat-plate collector by MorphoColor™ glass.

10. Acknowledgments

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11. References

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