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By
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Cover photo: Photo of the Heliac solar collector field at Lendemarke.
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Content

1. Introduction

The Danish company Heliac has developed a concentrating solar collector based on a unique and inexpensive polymer film. The film features a microstructure surface of Fresnel-lenses, which is applied to the backside of a float glass. Each collector consists of eight lenses mounted on a two-axis solar tracker, shown in Figure 1, which refracts the solar radiation towards a central focus point. The film can be manufactured using a novel roll-to-roll manufacturing method at a fraction of the cost of conventional solutions. Due to the low-cost lens and usage of standard components, the collector has the potential to deliver very low-cost heat.

However, two barriers were identified as limiting the commercial adoption of the technology:

- The lifetime of the original film was only 3-5 years, reducing the economic viability
- The current design features a number of safety concerns that have the potential to lead to injuries or cause material damage

To address these two barriers, the project "New silicone-based lenses for low cost concentrated solar heat" was initiated as a collaboration between Heliac, the Technical University of Denmark, Inmold, and E.ON. The project was financially supported by the Danish Energy Agency's Energy Technology Development and Demonstration Program under grant number: 64018-0606.

The aim of this report is to present parts of the results of the project, namely a comparison of the transmissivity of alternative lens materials and an investigation of the undesired focus spots produced when not in tracking mode.

Figure 1. Illustration of the Heliac solar collector (Source: Heliac).

2. Lens transmissivity

The original lens developed by Heliac was made of a PET-PP thermoplastic film mounted on the backside of a 4-5 mm thick window glass. As the glass was non-iron-free, most of the irradiation in the UV spectrum was absorbed, thereby protecting the film from UV degradation. While accelerated UV laboratory tests showed promising results, the lens degradation was found to be 5-10 times larger under actual outdoor conditions. Consequently, it was proposed to manufacture the lenses from a silicone resin with proven long-term durability.

A part of this project was to investigate the optical transmissivity of alternative lenses and assess the impact in terms of transmitted irradiance. To this end, the optical transmissivity, i.e., the fraction of light that passes through the glass and lens material, was measured. Tests were also carried out for two glasses without any lens material, denoted plain glass.

The transmission measurements were made for the following samples:

- Plain glass without anti-reflective coating
- Plain glass with anti-reflective coating
- Glass with a layer of polypropylene without anti-reflective coating (original design)
- Glass with a layer of silicone (v2) and anti-reflective coating
- Glass with a layer of silicone (v3) and anti-reflective coating

2.1 Spectrometer

The transmissivity measurements were made with a Cary 50 spectrophotometer, shown in Figure 2. The spectrometer is able to measure in the range of 190 to 1100 nm. The core of the instrument is a Xenon lamp that flashes 80 times a second and a beam splitter that only emits at the desired wavelength band. The transmissivity of the medium under test is then calculated as the ratio of the photons sensed by the detector relative to the emitted photons.

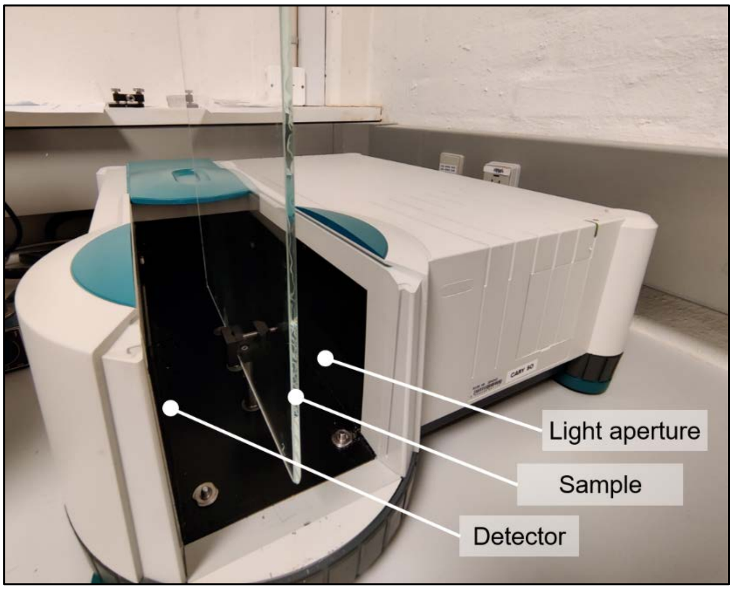

Figure 2. Photo of the Carey 50 spectrometer with a plain glass sample installed.

Before each measurement series, a baseline correction was applied to the spectrometer. This was done by measuring the detected output without any medium (100% transmissivity) and with the sensor blocked (0% transmissivity). The baseline correction ensures that any drift over time in the spectrometer is accounted for. As the chamber of the spectrometer had to be kept open due to the large sample size, the measurements were carried out with the lights in the room off, to eliminate any stray light hitting the detector. Additionally, the instrument's slow scanning mode was selected to achieve high accuracy and wavelength resolution. The slow scanning mode makes discrete measurements every 0.5 nm and scans at a rate of 300 nm/min.

2.2 Transmissivity measurements

The spectral transmissivity for the five different samples is shown in Figure 3. As expected, the plain glass with the anti-reflective (AR) coating performs the best. Utilization of the anti-reflective coating gives a higher transmissivity for wavelengths higher than 340 nm. The increase in transmissivity is 3.5 percentage points on average for wavelengths higher than 340 nm. For wavelengths lower than 340 nm, the anti-reflective coating induces a slight decrease in the transmissivity; however, this is of little importance as there is relatively little energy in the solar spectrum in this region.

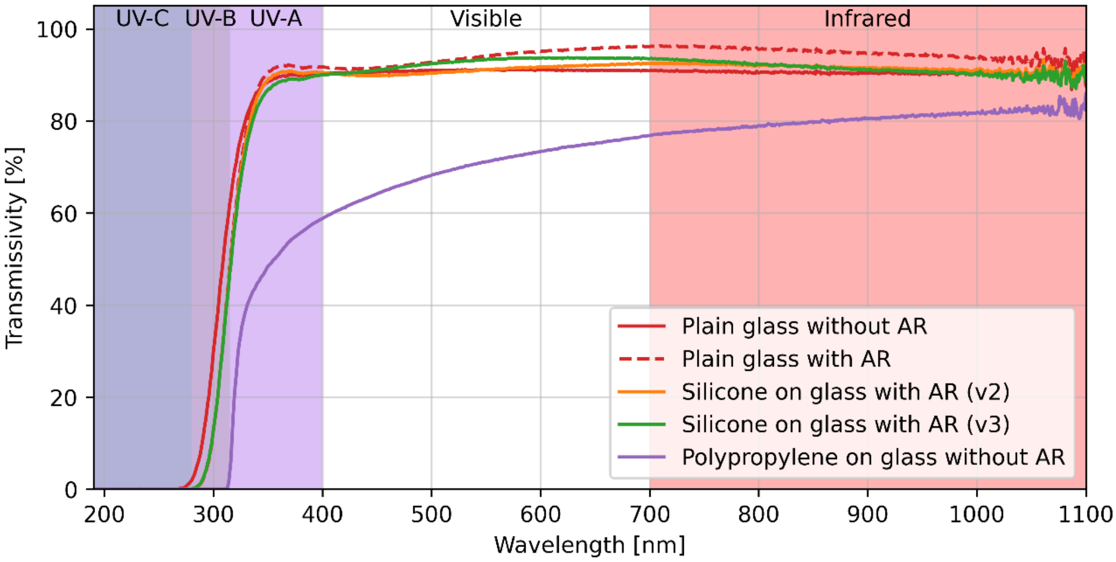

Figure 3. Transmissivity measurements. Background color denotes the different parts of the spectrum.

Furthermore, the transmissivity of three samples of glass with a thin layer of material was tested. One of the samples was a plain glass with a layer of polypropylene (PP) corresponding to the original lens, whereas the other two samples had a layer of silicone with slightly varying properties. The thickness of the layer corresponds to the average thickness of the Fresnel-lens structure of the full-size lenses. Hence, the measured transmissivity of the samples approximates that of the full-scale lenses, though it does not account for lens losses that vary with the diameter.

As shown in Figure 3, the original lens made of PP had a very low transmissivity. In comparison, the two samples with silicone on glass had a much higher transmissivity than the original lens, also when accounting for the original lens not having an anti-reflective coating. While silicone was initially selected due to its proven durability, the measurements show that silicone also has significant optical benefits. In contrast, the difference between the two types of silicone was relatively small, with the silicone v2 version showing a slightly higher transmissivity (0.4 percentage points on average for wavelengths greater than 340 nm). Besides an overall higher transmissivity, silicone is also transparent at much lower wavelengths than the PP lens and allows for a larger portion of the UV radiation to be utilized.

From an energy perspective, the spectral transmissivity is worth considering because the irradiance from the sun is not spectrally flat. Therefore, it is useful to quantify the transmissivity with respect to the solar spectrum. Since the solar spectrum constantly changes depending on sun position and atmospheric conditions, reference spectrums are generally used to achieve reproducible performance comparisons. In this study, the ASTM G-173 reference spectrum is used, as shown in Figure 4. As lenses only concentrate the direct and circumsolar irradiance, this spectrum is used.

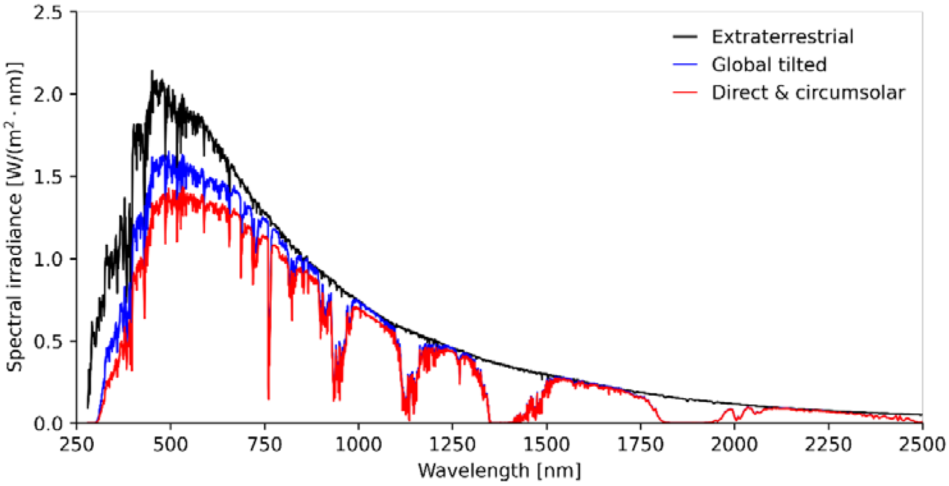

Figure 4. ASTM G-173 reference spectrum (air mass 1.5)

To assess the fraction of irradiance transmitted through the samples, the transmissivity shown in Figure 3 is multiplied by the 'Direct and circumsolar' reference spectrum shown in Figure 4 and divided by the total irradiance of the spectrum. The effective transmissivity, which accounts for the sun's spectrum, can then be obtained by summing the weighted transmissivity. The effective transmissivity for the five samples is listed in Table 1.

Table 1. Effective transmissivity of the various lens samples (considering 280 to 1100 nm).

Lens sample	**Effective transmissivity**
Plain glass without AR	90.6 %
Plain glass with AR	94.1 %
Glass with a layer of silicone (v2) and anti-reflective coating	91.2 %
Glass with a layer of silicone (v3) and anti-reflective coating	91.9 %
Polypropylene (PP) on glass without AR	73.6 %

Based on the effective transmissivity values shown in Table 1, it is evident that the silicone lenses transmits approximately 25 % more solar irradiance than the original polypropylene lens. This is a huge increase, which means that manufacturing the lenses from silicone will result in the collector having a much higher optical efficiency, and thereby a greater annual energy output. The results in Table 1 also show the benefit of using an anti-reflective coating in terms of increased energy yield, and this information is critical when deciding if its use is economical.

3. Off-axis intensity

The primary safety concern of the original collector was the generation of undesirable off-axis focus spots whenever the collectors were not tracking the sun. While in most cases, the collectors are tracking, there are certain times when this is not possible, e.g., during periods with high wind gusts where the collectors are stowed in the horizontal position. In such situations, the solar irradiance hits the lens at a non-90 degree angle, and the sunlight is focused outside of the receiver, either on the ground or on the collector itself. These off-axis focus points can reach significant irradiance levels and damage the collector or set the surrounding vegetation on fire.

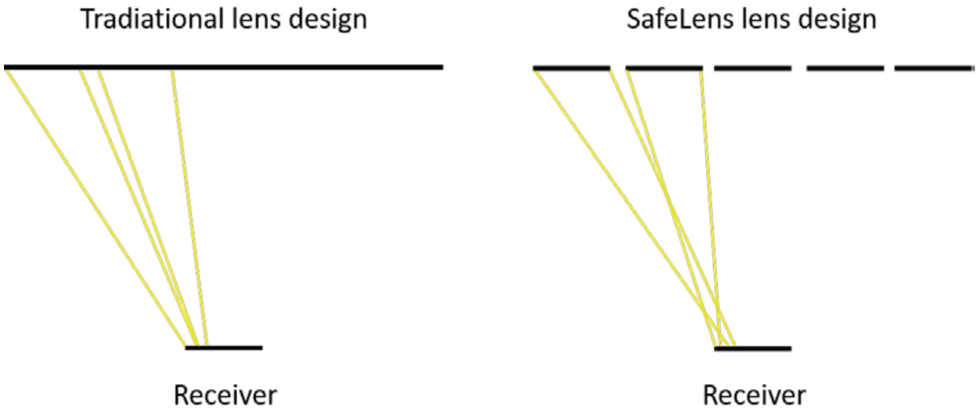

Figure 5. Illustration of the SafeLens lens design.

To this end, Heliac has proposed a new lens design that reduces the intensity of the off-axis focus points, thereby limiting the risk of accidents. In traditional Fresnel lenses, the lens refraction angle increases gradually with increasing distance from the center, and hence the light rays never cross (see Figure 5). In contrast, the proposed SafeLens design divides the Fresnel-lens into different sections that focus on different areas of the receivers. While this causes a marginal increase in optical losses, it significantly reduces the off-axis focus points. The SafeLens lenses located at the outdoor test facility at the Department of Civil Engineering are shown in Figure 6.

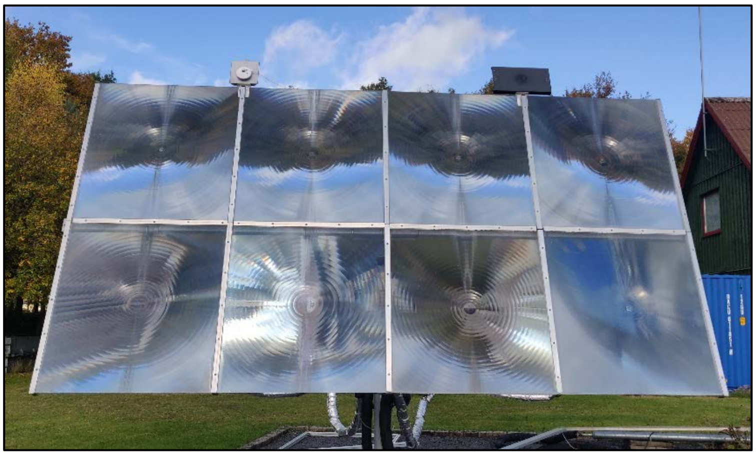

Figure 6. Photo of the Heliac collector with SafeLens lenses.

A part of this project was to investigate and document to which extent the SafeLens lens concept reduces the off-axis focus points. A measurement campaign was carried out to assess this, measuring the intensity of the off-axis focus points for the original lens and a lens featuring the SafeLens design.

3.1 Measurement setup

Traditional pyranometers used to measure irradiance are only suitable to measure up to 2000 W/m^2, which is much higher than naturally occurring solar irradiance. The off-axis focus points, however, had an irradiance intensity much higher than this. Therefore, a custom sensor was built (shown in Figure 7) which was able to measure under heightened irradiance conditions.

The core of the sensor was a silicon photodiode pyranometer (Apogee SP-110), which was chosen due to its fast response time (< 1 ms). A filter was installed in front of the lens to reduce the irradiance of the off-axis focus points to be within the sensor's operating range (0-2000 W/m^2). The filter used was a shade number 5 welding glass, with a transmissivity of approximately 2%, meaning the incident irradiance was reduced by a factor of 50.

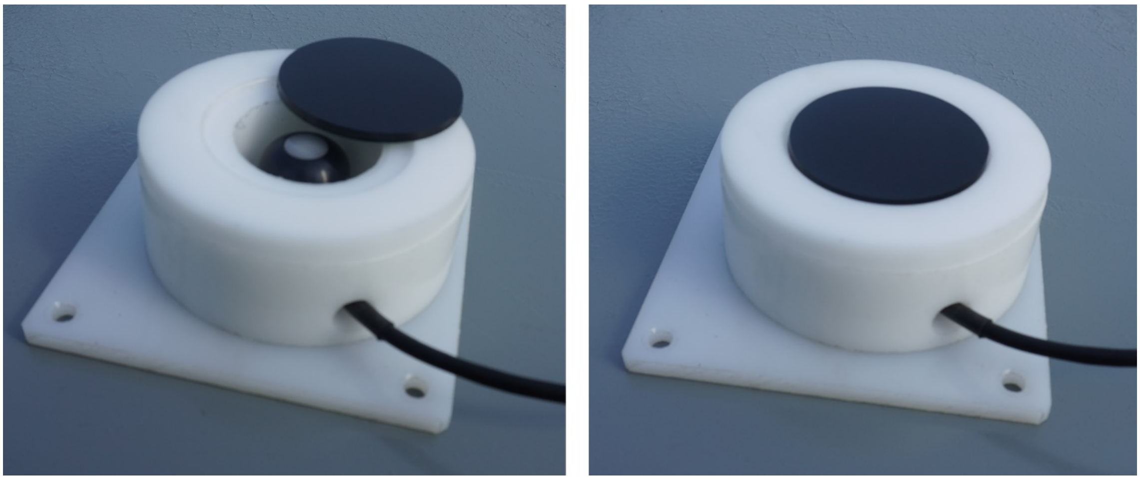

Figure 7. Photo of the irradiance intensity measurement setup. The uncovered photodiode irradiance sensor (left) and the sensor with the filter glass installed (right).

3.2 Measurements

During the measurement campaign, the collector was placed in the horizontal position. Also, the collector was rotated such that the sun vector aligned with the diagonal of the lenses, as this resulted in the highest intensity. Photos of the off-axis focus points generated by the four lenses tested are shown in Figure 8.

Figure 8. Photos of the off-axis focus points for the different lenses.

The irradiance intensity of the off-axis focus points was then measured using the custom sensor described in the previous section by placing the sensor horizontally in the center of the focus point. To ensure that the sensor measured the focus point, the sensor was moved around within a distance of approximately 10 cm, and the highest irradiance value was recorded.

As this investigation aimed to compare the different lens designs, the off-axis focus point intensity is presented in relative values. Measurements were made over three different days with clear sky conditions, and a total of 5 measurements were made. The measurements are presented in Table 2.

Table 2. Off-axis focus point measurements. All measurements are relative to lens 1.

Experiment no.	**Date**	**Time**	**Off-axis intensity (relative to Lens 1)**			
			1 SafeLens v3	2 SafeLens v3	3 SafeLens v2	4 Original PP
1	30-05-2021	12:43	100%	94%	52%	46%
2	30-05-2021	15:14	100%	91%	62%	49%
3	30-05-2021	16:40	100%	90%	65%	50%
4	31-05-2021	14:57	100%	95%	61%	44%
4	02-06-2021	13:10	100%	97%	54%	48%
5	02-06-2021	13:25	100%	93%	54%	40%
Average			100%	93%	58%	46%
Std. dev.				2%	5%	3%

Note that two of the lenses tested were identical, which provides information about the method's reproducibility. Comparing the two identical lenses (1 & 2), it can be seen that there is a 7 % average difference in the off-axis focus point intensity. This difference can be due to a variation in the soiling of the lenses (which reduces the transmissivity), variation in manufacturing imperfections, or how well the focus point was identified. Nonetheless, the method is considered sufficiently reliable given the spread in the measurements of the other lenses is much higher.

Overall, three different types of lenses were tested, namely SafeLens v3, SafeLens v2, and the original PP lens. The two SafeLens versions differ in how wide the sections of continuous Fresnel lens refraction angles are. The SafeLens v2 features an aggressive design, which is expected to result in relatively low-intensity off-axis focus points, but at the cost of higher optical losses. In contrast, the SafeLens v3 features a compromise between the traditional Fresnel lens design and the SafeLens design, still resulting in a significant reduction of the off-axis intensity, but without compromising the optical efficiency of the lens. The measurements in Table 2 confirm these design choices, i.e., the more prominent SafeLens lens (v2) reduce the intensity of the off-axis focus points by 42 % on average compared to the lesser aggressive v3 version. Compared to the original PP lenses, the off-axis intensity is higher for both types of SafeLens lenses. However, the higher intensity of the Safelens lenses is due to the higher optical transmissivity (as shown in Section 2.2) and not as a result of the lens design.

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