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Freiburg, July 17, 2019

Report on Evaluation of Luminescence Solar Concentrator Technology from GlasstoPower

Dear Prof. Brovelli,

Please find enclosed our report on the outcome of evaluating the Luminescence Concentrator Technology from GlasstoPower based on the Technical Report received June 2019.

Best Regards

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FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME ISE

Report

EVALUATION OF TECHNOLOGY CONCEPT AND CHARACTERIZATION METHODS

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Freiburg, 17.07.2019

Prepared for: GlasstoPower, Italy

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1
Evaluation of technology / overview

1.1 Preliminary remarks

GlasstoPower aims to commercialize a new type of photovoltaic glass. Based on the experience from Fraunhofer ISE in a similar technology the technology concept, the applied characterization methods of Glass2Power have be evaluated and are presented in this report. GlasstoPower has provided Fraunhofer ISE with a description of their technology on the basis of an earlier signed NDA and a report dated from June 2019 as well as on the basis of two emails from 26.6 and 29.6.2019. In the following, references will be made to the figures in the report from GlasstoPower.

1.2 Overall evaluation of technology

The technology of GlasstoPower relies on the principle of luminescent solar concentrators (LSC). LSC have been studied since 1982 as an alternative to geometrical concentrators like mirrors or lens systems[1-4]. The theoretical advantage of a LSC compared to other concentrator systems is their ability not only to concentrate direct light but also to concentrate diffuse light. This ability to concentrate diffuse light is achievable through the use of molecules or, like in the case of GlasstoPower nano-particles, with high light absorbing and high light emitting properties also known as luminescence. The emitted light is trapped inside the waveguide to about 70% which in particular consists of a thin glass or plastic glass sheet and led to the edges.

The highest efficiency of a LSC can be realized with a material having a broad band light absorption spectra, ideally of rectangular shape and a very narrow band luminescence spectra which is slightly red-shifted with no spectral overlap to the absorption spectra. With existing materials the complete spectral separation of absorption and emission is very difficult to achieve which leads to efficiency losses in larger size LSC due to reabsorption of the emitted light.

The luminescent silicon and CuInZS2/ZnS nanoparticles introduced by GlasstoPower show a broad absorption and only a small spectral overlap with the luminescence spectra which represents an important step towards higher efficient large size LSC. As the silicon and CuInZS2/ZnS nanoparticles emit in the invisible near infrared there exists also a further benefit over previous LSC concepts using organic molecules emitting in the visible part of the spectra. In the latter case the visible luminescence gives the LSC an appearance of a "colored haze" which represented a disadvantage for the application as architectural window glass. In contrary, the LCS from GlasstoPower show a very good visible transmission without disturbing haze as is demonstrated in the photos of the report.

The optical quality of the plate of a LSC, which is acting as the waveguide for the emitted light, plays an important role for the efficiency. It has therefore to be guaranteed, that by incorporation the luminescent nanoparticles into the matrix of the plate no chemically induced deterioration of the optical quality is occurring. Here GlasstoPower has successfully developed a suitable process which is not altering the polymethylmethacrylate matrix.

2
Evaluation of characterisation methods (part 1)

2.1 Structural properties of CuInZnS2/ZnS NCs

2.1.1 Particle Size Homogeneity

The photo-physical properties of luminescent nano-particles and in-particular the spectral width of the luminescence spectra depends on the size of the particles. Here, a narrow particle size distribution in the lower nanometer dimension is necessary. The determination of particle size distribution using transmission electron microscopy (TEM) as in the shown case of luminescent CuInZS2/ZnS nanoparticles (**figure 1**) from GlasstoPower is an appropriate method.

2.1.2 Crystal structure

The knowledge of the crystal structure is important during synthesis of nano-particles for identification and quality control. X-Ray diffraction (**figure 2**) of the synthesized nano-particles in comparison to reference substances represents the appropriate method here.

2.2 Optical properties of core-shell CuInZnS2/ZnS NCs

2.2.1 Absorption and Photoluminescence properties

The determination of the overlap between the absorption and the luminescence spectra of a LSC is necessary to calculate the optical efficiency and to understand the degree of light lost in the LSC due to reabsorption in larger sized plates. Additionally the absorption spectra of the matrix (here polymethylmethacrylate) in the spectral region of the emitted light is necessary to understand further losses due to absorption in the matrix. **Figure 3** shows the results from the appropriate optical characterization.

2.3 Batch Reproducibility

In a later industrial production of GlasstoPowers LSC the quality control is important. In particular the batch-to-batch reproducibility of the luminescent nano-particles is crucial. As determined from the absorption and luminescence spectra measurement (**figure 4**), the photoluminescent quantum yield and the determination of the peak position in the luminescence spectra are the necessary quality control methods to control the reproducibility between batches. The quantum yield has direct influence on the LCA efficiency, whereas the peak position is sensitive to variations in the particle size.

3
Evaluation of characterisation methods (part 2)

3.1 Poly (methyl methacrylate) (PMMA) Nanocomposites

3.1.1 Polymer Chain Dispersity

GlasstoPower is using polymethylmethacrylate as the polymer matrix in which the luminescent nano-particles are incorporated in this process. The polymerization process might be influenced resulting in unwanted side reactions or optical and mechanical changes. The gel permeation chromatography (GPC) is a suitable analysis tool to determine and to compare the polydispersity of the polymers in the LCA-polymer nanocomposite (**figure 6**) with those of the undoped polymer plate.

3.2 Polymer chain composition: NMR analysis

As mentioned above, unwanted interactions between the nano-particles and the polymer matrix have to be prevented. An unwanted reaction would be the hindering of polymerization leaving back unreacted monomer. 1H NMR analysis (**figure 7**) represents a suitable characterization method here.

3.3 Differential scanning calorimetry

To study thermally induced reactions by the luminescent nanoparticles in comparison to pure polymer samples a suitable method here is the differential scanning calorimetry applied by GlasstoPower for this purpose (**figure 8**)

3.4 Optical properties of the PMMA nanocomposites embedding the core-shell CuInZnS2/ZnS NCs

3.4.1 Absorption and photoluminescence characteristics

For the optimization and the calculation of the solar efficiencies of the LCA the optical absorption spectra and the luminescence spectra have to be recorded for the nanoparticles in solution and after incorporation into the LCA polymer Matrix. Also the optical absorption in the polymer matrix in the spectral region of the emission has to be determined to account for efficiency losses caused by the overlap between absorption and emission (luminescence) spectra. This method as used by GlasstoPower is therefore appropriate (**figure 9**).

3.4.2 Optical quality: Waveguide Color

For the application field of architectural glass it is important to reach a color neutral optical appearance of the LCS. GlasstoPower uses here the appropriate standardized method (**figure 10**) to determine the color co-ordinaties based on transmission measurements.

3.4.3 Optical quality: Color rendering index of transmitted sunlight

Equivalent remarks as for s.o. (**figure 11**)

3.4.4 Optical quality: Indoor-to-outdoor chromatic perception

Equivalent remarks as for s.o. (**figure 12**)

3.4.5 Optical quality: Suppression of light scattering losses

Scattering of luminescent light can present an important loss factor in LSC and has to be prevented. The determination of a plateau like optical absorption effect in the spectral region of the luminescence using a transmission photo-spectrometer in direct transmission mode is the appropriate method here. The spectra has to be carefully corrected for “baseline” effects of the used photo-spectrometer (**figure 13**).

3.4.6 Optical quality: Absence of light scattering losses

The measurement of the baseline in absorption caused by light scattering (s. 3.4.5) gives a first indication about the real loss due to light scattering in a LSC. Therefore another characterization method is used by Glass2Power which can directly be applied to LSCs with various size (**figure 14**). Here, the LSC sample is placed in an optically integrating sphere and the luminescence excited. By comparing the data received from samples with open edges and blackend edges the amount of luminescent light leaving the plate in the “escape cone” (face emission), the amount of luminescent light leaving the concentrator edges (edge emission) and as the sum the total emission can be derived and the light trapping efficiency can be compared to the theoretical value. This method gives a good indication of unwanted luminescent light loss caused by hindered re-emission and light scattering.

3.4.7 LSC waveguiding performance

Yet, another independent charcterisation method has been applied by GlasstoPower to determine the loss of light during its way from an illuminated spot to the edges of the LSC plate as a function of the spot distance to the edge. This method is an appropriate way to gain information of the waveguide performance. At the edge of the LSC the luminescence spectra is recorded (**figure 15 a**). By integrating the spectra as a function of distance a measure for the light output can be derived (**figure 15 b**). Here, an important issue to be considered is, that the integration has to be performed over the full spectra range of the luminescence spectra.

4
LSC solar window device

For the targeted application of the LSC from GlasstoPower, architectural glass for building integrated photovoltaics, it is necessary to test and to determine the solar to electrical conversion efficiency of the whole system, i.e. the LSC plate mounted inside an insulation window frame with solar cells adjusted to the edges of the LSC plate. Further detail about the outdoor set-up and the measuring conditions (intensity of sunlight, angle, distance to the ground etc) had been provided in an e-mail from 26-6-2019). An outdoor test-stand has been installed at Glass2Power (**figure 16**). The set-up allows continuous monitoring of the electrical output of the LSC device in comparison to a reference silicon solar cell module which is the appropriate method in outdoor photovoltaic module monitoring. The LSC device is oriented vertically.

4.1 Device performance

From the measurements at the test-stand at 0.8 sun intensity and the pre-determined luminescence spectra three figures of merit have been calculated and present in the table. For the application the first value, i.e. the solar to electrical power conversion efficiency is most important. Here, in addition measurements at different light intensities and illumination conditions like direct and diffuse sunlight could be beneficial to be presented in addition. The other two performance indicators optical power efficiency and optical quantum efficiency are only indirectly related to the future market but are important fot the further optimization of the luminescent nano-particles and the polymer waveguide plate.

4.1.1 Operational stability

For the final extrapolation of the long-term stability of the LSC device under real conditions, continuous illumination tests should be carried out for a longer time than the presented 120 hours. Also, in the future standard tests according to the norms for photovoltaics modules and related to norms from building construction will have to be carried out.

5 Evaluation of characterisation methods (part 3)

5.1 Silicon Nanocrystals

5.1.1 Absorption and Photoluminescence properties

(**figure 18**) Same comments as for 3.4.1

5.1.2 Optical properties of the polymer:NCs nanocomposites

(**figure 19**) Same comments as for 2.2.1

5.1.3 Optical quality: absence of scattering losses

(**figure 20**) Same comments as for 3.4.6

6
Conclusion

All the characterization methods described in the technology report from GlasstoPower presented are appropriate for either the optimization or quality control as well as for the determination of the solar efficiencies of the LSC devices under real conditions.

6.1 Explanation of abbreviations

LSC	Luminescent Solar Concentrator
NC	Nano colloidal particles
NDA	Non Disclosure Agreement
NMR	Nuclear Magnetic Resonance
X-ray	High energy photon scattering
NIR	Near Infrared

6.2 References

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