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Review of the doctoral dissertation

by MSc Fabian Schoden entitled: "Investigation of non-toxic dye-sensitized solar cell materials for circular design approaches"

The formal basis for the submission of this review is the resolution of the Council of the Discipline of Materials Engineering at the Silesian University of Technology dated October 24, 2023, no. 150/2023, appointing the reviewers of the dissertation.

Assessing the rationale for addressing the topic

The topics of the doctoral dissertation include technologies critical to the economy: A closed-loop economy in the area of renewable energy conversion equipment.

In an era of depleting energy resources and increasing pollution environment, the use of energy from renewable sources and the reduction of the use of toxic and harmful materials, are becoming a necessity. Recycling and reuse of materials is a key part of holistic eco-design, which takes into account efficiency, lifetime, energy payback period (EPBT - Energy Payback Time), safety and material availability.

Dye Sensitized Solar Cells (DSSCs) are - in unlike the dominant photovoltaic modules on the market based on crystalline silicon technology (monocrystalline and polycrystalline) - are based on silicon-free technology, using functional materials such as metal nanoparticles and metal oxides, organic dyes or conductive polymers. These cells are inexpensive, easy to manufacture and can withstand long exposure to light and heat compared to traditional silicon-based solar cells. Although they are not very efficient, they are very effective in a wide range of sunlight conditions.

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In his dissertation, Fabian Schoden, M.Sc., took up the current problem of developing a technology for manufacturing this type of cell, using only non-toxic materials, with low energy requirements at the production stage.

For the reasons outlined above, I consider it justified to take up the topic considered in the paper justified.

Substantive evaluation of the work

The doctoral dissertation presented to me for review was written under the scientific direction of scientific supervision of Prof. Tomasz Błachowicz (Silesian University of Technology) and Prof. Dr. ing. Eva Schwenzfeier-Hellkamp (HSBI Hochschule Bielefeld) and performed at the Silesian University of Technology.

The doctoral student formulated and proved the following hypothesis: *materials for manufacturing DSSC cells, can undergo cyclic technological processes so that the obtained stability of the structural, optical and electrical parameters, gives the possibility of their reuse use in photovoltaic devices.*

In the paper, Fabian Schoden, M.Sc., focused on conducting experiments, indicating the possibility of reusing materials, used in the manufacture of DSSC cells (recycling) or regeneration of cells. Consequently, he presented the economic justification for realizing a closed loop in the production and use of photovoltaic dye-sensitized cells.

The work consists of six essential chapters: Introduction, Theoretical basis, Methodology, Experimental results, Discussion, Summary and Conclusions.

The dissertation has a total of 182 pages, with 74 figures and 11 tables. The structure of the work is correct, and the layout of its content - clear. The cited literature is extensive, the index contains 171 literature items, including references to websites.

In the literature part, the doctoral student presented an analysis of available information, which can be of importance in the design of recycling and regeneration technologies, as well as processes for the production of dye cells, enabling such subsequent handling of them, supportive to environmental protection. Important from this point of view are the experiences gained from the analysis of recycling methods for crystalline silicon photovoltaic cells.

The experimental section discusses the analytical methods and measurement techniques used in carrying out the work.

Cells manufactured between 2018 and 2020 (2-3mm thick glass substrates) were tested for recycling.

On the other hand, regeneration studies were conducted on cell samples: made on commercially available glass substrates with TiO_2 layers, samples made on substrates recovered from used cells with hand-applied layers, and samples of older cells - dating back to 2015, regenerated with an electrolyte, with the addition of a new TiO_2 layer on top of the original layer, and with the replacement of the old TiO_2 layer with a new one.

Cell conversion efficiency (PCE) was studied under STC conditions, using the LS0500 solar simulator made by LOT-Quantum Design GmbH.

The doctoral work presented here is a documentation of a comprehensive study aimed at identifying potential opportunities for regeneration and recycling of dye cells to realize the circular economy approach. It should be noted that in the course of the dissertation, the doctoral student used various measurement methods. On the basis of the analysis of the results obtained, he formulated conclusions that served to verify the assumptions made.

In my opinion, the original achievement of the work is:

- proving the stated thesis as a result of the planned and independently conducted experiments,
- performing studies by various methods, including scanning electron microscopy SEM-EDX, inductively coupled plasma optical emission spectroscopy ICP-OES, using atomic force microscopy,
- demonstrating that remanufacturing and recycling processes can be developed into manufacturing processes that meet the principles of a closed-loop economy; applying the CIRCO method, which is based on the achievements of researchers at Delft University of Technology and is called "Products That Last" - it includes five closed-loop business models and six closed-loop design strategies.

The results of the research conducted by the Doctoral Student have been published in 5 articles in scientific journals, in 4 of which the Doctoral Student is the first author:

- Fabian Schoden, Marius Dotter, Dörthe Knefelkamp, Tomasz Blachowicz, and Eva Schwenzfeier-Hellkamp. Review of State of the Art Recycling Methods in the Context of Dye Sensitized Solar Cells. Energies, 14(13):3741, 2021.
- Fabian Schoden, Anna Katharina Schnatmann, Emma Davies, Dirk Diederich, Jan Lukas Storck, Dörthe Knefelkamp, Tomasz Blachowicz, and Eva Schwenzfeier-Hellkamp. Investigating the recycling potential of glass based dye-sensitized solar cells - melting experiment. Materials, 14(21):6622, 2021.
- Fabian Schoden, Joscha Detzmeier, Anna Katharina Schnatmann, Tomasz Blachowicz, and Eva Schwenzfeier-Hellkamp. Investigating the Remanufacturing Potential of Dye-Sensitized Solar Cells. Sustainability (Switzerland), 14(9):5670, 2022.
- Fabian Schoden, Anna Katharina Schnatmann, Tomasz Blachowicz, Hildegard Manz-Schumacher, and Eva Schwenzfeier-Hellkamp. Circular Design Principles Applied on Dye-Sensitized Solar Cells. Sustainability (Switzerland), 14(22):15280, 2022
- Anna Katharina Schnatmann, Fabian Schoden, and Eva Schwenzfeier-Hellkamp. Sustainable PV Module Design - Review of State-of-the-Art Encapsulation Methods. Sustainability (Switzerland), 14:9971, 2022.

I rate this achievement as good.

Comments of a substantive nature

- Please comment on the cells selected for the recycling study - why was such a choice made and can this material be considered representative of different cells (different manufacturers and from different periods of production) - please comment on the cells that have been remanufactured.
- What was the composition of the H_2SO_4 + HF digestion mixture and what supports this choice of digestion solution?
- What was the participation of the Doctoral Student in the studies performed (which studies were performed by himself, which were performed with his participation or which were eventually commissioned)?

- What problems are posed by the different chemical composition of glass in recycling processes?
- Isn't the very low value of the PCE coefficient obtained (on the order of 0.025%) within the measurement error? Please provide an analysis of the measurement error.
- Most of the tools of the Circo method are qualitative in nature. Has the PhD student analyzed using other methods that allow for quantitative analysis, such as the Environmental Life Cycle Assessment (LCA), which is also a technique from the field of management and allows for the assessment of potential environmental risks, providing the opportunity to compare the process without and with recycling.

Remarks of an editorial nature

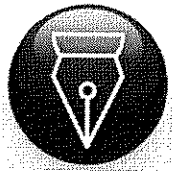
Like any work, the dissertation is not free of stylistic and punctuation errors, but this does not affect my high rating of the editorial side.

- The presented literature list does not include a DOI (Digital Object Identifier), which would facilitate quick access to articles.
- Pg. 142 item [92] Michael Tupy, Pavel Mokrejs, Dagmar Merinska, Petr Svoboda, and Josef Zvonicek. Windshield recycling focused on effective separation of PVB sheet, 2014 - incomplete data, no journal title.
- Items [16] and [18] (p.133) are duplicated.
- Figure 1 on page 11 and Figure 2 on page 44 are from the article: *Jan Lukas Storck, Marius Dotter, Bennet Brockhagen, and Timo Grothe. Evaluation of Novel Glycerol/PEO Gel Polymer Electrolytes for Non-Toxic Dye-Sensitized Solar Cells with Natural Dyes Regarding Long-Term Stability and Reproducibility. Crystals, 10:1158, 2020*, and not from: *Fabian Schoden, Marius Dotter, Dorthe Knefelkamp, Tomasz Blachowicz, and Eva Schwenzfeier-Hellkamp. Review of State of the Art Recycling Methods in the Context of Dye Sensitized Solar Cells. Energies, 14(13):3741, 2021.*
- Why does the sentence in the 1st paragraph from the bottom on page 13 refer to the [26]: Jan Lukas Storck, Marius Dotter, Bennet Brockhagen, and Timo Grothe. Evaluation of Novel Glycerol/PEO Gel Polymer Electrolytes for Non-Toxic Dye-Sensitized Solar Cells with Natural Dyes Regarding Long-Term Stability and Reproducibility. Crystals, 10:1158, 2020?

Final conclusions

In summary, the reviewed doctoral dissertation is an original solution to the scientific issue undertaken. In it, the author has considered a problem that is of significant cognitive and economic importance. He has correctly defined the assumptions for its analysis and successfully implemented them. In carrying out his argumentation, he demonstrated a good knowledge of general theoretical issues, as well as the ability to conduct scientific work independently, including research using various methods.

I express my appreciation for the contribution of the doctoral student's work, and I would like to emphasize the high scientific significance of the results obtained and evaluate the doctoral dissertation reviewed by me very positively. At the same time, I conclude that the work of MSc Fabian Schoden fully meets the requirements for doctoral dissertations by the Law on Academic Title and Degrees, and I hereby request that it be admitted to public defense.



Signed by /
Podpisano przez:

Ewa Klugmann-Radziemska
Politechnika Gdańska

Date / Data:
2023-12-04 11:36