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REVIEW OF THE DOCTORAL DISSERTATION

by MSc Fabian Schoden

Investigation of non-toxic dye-sensitized solar cell materials for circular design approaches

Promoters:

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1. Topicality and originality of the subject matter and the thesis and purpose of the dissertation

The dissertation presented concerns a comprehensive analysis of the possibility of using DSSC solar cells in the circular economy cycle. The doctoral student undertook a task of great importance for the operation of photovoltaic installations in the modern power generation system, which is the possibility of regeneration, utilization and recycling of solar cells. For this purpose, the author has chosen dye-sensitized solar cells (DSSCs), which are currently a niche part of photovoltaic structures and their efficiency is far from the records obtained in terms of inorganic cells, but due to their design, they offer the possibility of achieving a low-carbon production process.

In the case of the introduction of this type of construction to the market, the possibility of reuse and recycling of such elements will ensure a fully environmentally friendly product cycle, and from this point of view it is very important for the further development and implementation of photovoltaic technology. For the above reasons, I consider the topic as timely and important. At the same time, it should be recognized that this is an original research topic, as there are no defined closed-loop procedures for solar cells with organic components.

2. Dissecting the task at hand - the author's methods and independence

In his work, the author has used varied technical and economic analysis tools of the adopted research problem, using, as a background, the existing processes developed for silicon cells. This is fully justified, as silicon technology now represents not only more than 90% of the photovoltaic market, but is also the most commercially matured photovoltaic technology. This made it possible to develop procedures for the interchangeable processing of silicon modules, the oldest of which are already past their exploitation cycle. At the same time, the dye-sensitized cell technology studied by the Ph.D. student is characterized by a shorter lifetime and, as such, will require faster efforts aimed at developing recycling processes.

An important and noteworthy element of the completed research plan is the comprehensive approach to the problem posed, consisting both in the study of technological processes for the reprocessing and remanufacturing of used DSSC cells and in the economic analysis and attempt to build a business model for such a process. This is, of course, a very broad task and goes beyond the scope of the presented dissertation, but the presented results can provide an important interdisciplinary input for the development of appropriate procedures and models in the future. While appreciating the importance of the research undertaken, it is however also important to point out certain shortcomings, resulting in part from the very extensive scope of the work carried out, as well as its great innovation.

It is worth noting that the author uses a new tool for analyzing the available literature, using the VOSviewer program. This is important because the doctoral student uses the software tool not only for a more efficient analysis of the available literature, but also to correctly define the scope of the research, which improves the purpose and value of the experiments and is a significant methodological innovation of the scientific workshop. With the help of the literature analysis conducted in this way, the author proves the growing interest in the research topic undertaken and defines the most important scientific problems. The research methodology adopted is appropriate to the topic and its description is clear and comprehensive. In the discussion of the results, the author refers directly and explicitly to the experiments indicated earlier.

An important achievement of the work is the formulation of a business model of the process of production, use and processing of DSSC cells on the basis of the results of technical experiments carried out, analysis of the business environment, as well as experience obtained from similar processes carried out for silicon cells and modules. I consider the author's original achievement to be especially the interpretation and use of the results of experiments on the regeneration and intermediate processing of DSSC cells to propose original models for their use by the end user, as well as to estimate the economic and environmental benefits of the various stages of this process.

An important element of the author's research work was also the publication of the obtained scientific results. The results presented in the dissertation have been largely published in international MDPI journals with impact factors from 3.2 to 3.9. The number of citations of the author's work in the Web of Science Core Collection database is 54 and the value of H index equals 5. This demonstrates the interest of the scientific community in the conducted

work and the importance of the achieved achievements. Although, some publications in journals of other publishers are mostly missing.

The presented work is formally correct and has a structure appropriate for doctoral dissertations. The structure of the work is clear and follows the commonly accepted IMRAD structure. The theoretical introduction presented corresponds to the topic of the work, although it is quite enigmatic and could be extended in some aspects - especially concerning the optoelectronic parameters of DSSCs and the aging mechanisms occurring in these devices.

I consider the following to be particularly valuable elements of the work:

- Synergistic use of technological steps and process analysis using circular economy (Circo) models.
- Using a new literature research methodology to determine the relevance and potential scope of the research topic.
- Application of modern tools for analysis of scientific literature (VOSviewer).
- Application conclusions, drawn from the analysis of experimental results.
- A cost-effective way of capturing the problem of the intrinsic cycle for organic DSSCs.
- Interdisciplinary approach to a complex technological problem, giving the possibility of a broader analysis of the studied issue and providing information on its real qualities of application.

Based on the factual observations, it can be concluded that the doctoral student has the ability to independently plan and conduct research experiments on the basis of the adopted scope of work, as well as the ability to publish the obtained scientific results in accordance with accepted standards.

3. The author's knowledge of the scientific field and the ability to present the results

On the basis of the presented results of the work and publications of the Doctoral Student, it can be concluded that he has obtained extensive knowledge in the discussed field and the following research skills:

- Comprehensive planning and conduct of interdisciplinary scientific research and selection of appropriate research tools in the field of theoretical analysis of the problem, statistics, conducting technological processes and analysis of results.
- Theoretical knowledge and practical skills in the production processes of dye-sensitized solar cells.

- Appropriate selection of research methods, operation of equipment and interpretation of results obtained by means of differentiated techniques of material, optical and electrical characterization of layers and semiconductor elements.
- Recognition and application of the industrial transformation processes used in the circular economy for photovoltaic elements.
- Ability to critically analyze the results of measurements, and prepare scientific publications.

4. Critical comments and objections to the content of the dissertation

The wide thematic scope of the work, as well as its interdisciplinary nature, places high demands on the doctoral student and creates an opportunity to make mistakes. The main shortcomings of the presented work include the manner of definition of the scientific goal.

The PhD student's defined purpose of the work, which reads: "to study the materials used in the production of DSSC cells that can be reused many times" is very vague. Likewise, the descriptive statement that so far there are no reports of experiments in the field of secondary processing, recovery of raw materials and the circulation model of DSSC cell components, as the author's accepted purpose of the work (p. 53). Such formulation of the purpose of the work is not precise and appropriate in a doctoral thesis. Such an objective could be the performance of experiments within a defined range, which are intended to lead to a specific effect - e.g. to prove the research hypothesis.

In addition, ones can't be agreed with the author's statement given in the justification of the topic that the low cost of manufacturing of silicon cells in China is solely due to changes in the technology of their production. There are more factors influencing the cost of silicon cell production in the Far East, such as the low cost of electricity from non-organic sources. The new EU directives address these factors and require that the cost of the energy-intensive manufacturing process be included in the product, which will further improve the competitive advantage of DSSC cells.

A significant shortcoming of the work is also the lack of discussion and analysis of the aging mechanisms of cells and modules and, in particular, DSSC cells, and their impact on changes in the parameters of PV cells and modules and the period of failure-free operation of these elements. Without knowledge of these phenomena, it is difficult to make a detailed assessment of the value of the proposed technologies for cell re-treatment.

More specific critical considerations include the following points:

1. No plotting of the full characteristics of the tested cell samples. The changes in the current-voltage characteristics and the resulting power characteristics give a better picture of the results obtained than the approximate numerical results shown collectively in one table (Table 4).

2. Section 2.3 is entitled "DSSC materials and functioning principle" and its subsequent subsections (2.3.1-2.3.6) deal with the components of DSSC cells and the materials used in their construction. In this view, it is incomprehensible to include in this chapter subsection 2.3.7, which deals with completely different types of cells - organic and perovskite cells. In addition, the discussion of two completely different original cell designs in one subsection is very perfunctory and meaningless. At the same time, these cells are not the subject of the author's research and are not within the scope of his further experimental work. This section should be presented separately, or - what seems more advisable in general - omitted, and the types of cells themselves should be placed only in the overview of photovoltaic designs placed in the introduction to the work.
3. The short-circuit current of a DSSC, denoted as Isc, and the short-circuit current density Jsc are two different quantities and should not be used interchangeably. In particular, the description of the determination of the value of the filling factor FF, located on page 74, should be corrected. In addition, the author in the list of symbols wrongly refers to Jsc as the short-circuit current of the cell, while to denote the voltage of the cell he uses in the work interchangeably the symbol U on page 70 (in the formula for the power of the cell) or V (list of symbols and other places in the work).
4. The drawings used do not always correctly fulfill the desired informative role and are not at the level corresponding to a scientific dissertation. Some drawings (e.g. Fig. 1, Fig. 4) are of low quality, while others, such as photographs of commonly used laboratory equipment (Fig. 9, 10, 11, 13, 14, 16) do not contribute much to the content of the presented research. Moreover, the presented laboratory equipment does not appear in the order of the list presented at the beginning of section 3.2.
5. Some of the drawings have not been placed in the right place in the work, which makes it difficult to receive and correctly analyze the results (e.g. Fig. 48, presenting the results described in section 4.3.5 has been placed in section 4.4.1 - probably only for editing reasons).

In addition, among the important issues that should be raised during the public discussion are the following questions:

6. How can the process of recharging DSSC cells with electrolyte proposed by the Author be implemented under industrial production conditions in normal use?
7. Why, in the Author's opinion, is it necessary to apply UV filters to DSSC cells in order to reduce the degradation of the TiO2 layer when the glass substrate will naturally play the role of such a filter?
8. What type of cells (manufactured in 2018 and 2020) were used for the study? Who was their manufacturer and what were their nominal/catalog data (or what were the original parameters of these devices measured directly after their production)?
9. The paper lacks an estimation of the costs of the various elements of the processes of treatment, injection processing and disposal of DSSC cell elements. Is the author able to estimate the costs of his proposed processes for the remanufacturing and disposal of dye-sensitized cells?

10. How can the author's research be related to the complete photovoltaic modules built on the basis of DSSC cells, taking into account their encapsulation with polymer layers and the aging mechanisms occurring in them?

5. Final evaluation

Despite the critical remarks presented in the dissertation, the results of the theoretical analysis presented in the dissertation, as well as the experimental work carried out, constitute an original solution to an important scientific problem, and also demonstrate the author's high general theoretical knowledge and confirm his ability to conduct scientific work independently. On this basis, I conclude that the reviewed dissertation meets the requirements of Articles 186 and 187 of the Law dated at July 20th, 2018. Law on Higher Education and Science (Journal of Laws of 2018, item 1669, with later changes), and I request that it be admitted to public defense.

Maciej Sibiński