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Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Aliya Glagoleva

PhD Program: Materials Science and Engineering

Title of Thesis: Development of kW Scale Hydrogen Energy Storage System

Supervisor: Prof. Keith Stevenson

Co-advisor: Dr. Vasily Borzenko

Chair of PhD defense Jury: Prof. Alexei Buchachenko *Email: a.buchachenko@skoltech.ru*

Date of Thesis Defense: 09 October 2018

Name of the Reviewer: Buchachenko Alexei

X I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** **Date: 08-09-2018**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense. *If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.*
Reviewer's Report
Reviewers report should contain the following items: • Brief evaluation of the thesis quality and overall structure of the dissertation. • The relevance of the topic of dissertation work to its actual content • The relevance of the methods used in the dissertation • The scientific significance of the results obtained and their compliance with the international level and current state of the art • The relevance of the obtained results to applications (if applicable) • The quality of publications The summary of issues to be addressed before/during the thesis defense

The main goal of the Thesis submitted was to provide the proof of the concept of energy storage systems integrating hydrogen storage with proton-exchange membrane fuel cell, as well as to estimate the perspectives of such systems as the storage components of isolated microgrids. Accomplishment of this goal faces a number of challenges associated to materials science, modeling of heat, pressure and energy balance, system engineering and assessment of economic viability of suggested solutions. Research results and conclusions presented in the Thesis indicate that these challenges have been properly addressed and the goal claimed has been mostly achieved.

Chapter 1 of the Thesis presents the overview of the known energy storage technologies, their advantages, drawbacks and relevant applications. The author tried to be as broad as possible in considering various energy storage options. This demonstrates deep knowledge and understanding, but, from the viewpoint of Thesis structure, poor relevance of this review to the research performed is a weak point of the Thesis presentation (see below). Indeed, there is a kind of logical break in coming to case of Yakutian Batamai village considered as a documented example of small-scale isolated energy grid with integrated solar-battery storage technology. Useful is the account of the metal hydride (MH) variety and the essence of the physico-chemical processes governing hydrogen sorption and desorption. Fundamental knowledge of the material properties, together with hints for hydrogen storage reactor designs, indeed provides the solid ground for the research accomplished. Only very basic information is given on the second important component of the proposed technology, proton-exchange membrane fuel cell (PEM FC). From an engineering viewpoint, however, it can be justified by the use of commercially available cell, a kind of "black box" device.

Chapter 2 describes the first prototype system, so-called H2Bio, which uses 175W commercial PEM FC (sometimes 200W power is referred to in the Thesis). The prototype system relies on the hydrogen supply from the tank and access to standard public water and electricity supplies. It basically serves as the proof for proposed MH reactor design based on the cerium doped $LaNi_5$ alloy and its integration with the fuel cell. While the author showed that the prototype works, its operation is not free from remarkable problems, including efficiency losses and unexpected shutdowns. To my opinion, analysis of the different working regimes, variations of operational parameters and assessment of the improvement is comprehensive and addresses the most important bottlenecks in the function of prototype system. In particular, the tests performed revealed irregular hydrogen intake that necessitates extra free volume to damp accidental hydrogen pressure drops at the interface of reactor and cell. The operational regimes of FC also revealed importance of a back-up battery for system startup, shutdown and support in case of high load demand. Low efficiency of FC was attributed to improper air temperature and humidity regimes. It brought the author to the consideration of the PEM FC air-cooling system efficiency and idea to use removed heat to facilitate hydrogen regeneration in MH reactor. It is one of the central points of the whole work as its realization promises one to avoid external heat supply.

Chapter 3 introduces the methodology for simulating the performance of the different batteries that accounts, among other factors, empirical description of efficiency function and degradation. Though the approach developed is efficient, economic and reliable, connection of this chapter to the mainstream of the Thesis research does not seem clear enough. Also, simulating and characterizing lead-acid, NiMH, NiCD and Li-ion batteries the authors did not make any comment on the novelty of the results (even in connection with the data presented in the chapter 1 as overview, Tables 1.1, 1.2). In addition, implications of the results to integrated MH-FC system are limited by the conjecture that back-up battery should be maintained at highest possible state of the charge and thus should be charged whenever external load permits. I consider proposed battery simulation methodology as important and useful research result, but the author may wish either to put it into the Thesis context more logically or present it as an Appendix.

Analysis of the temperature balance of the commercial 1100 W PEM FC and the regimes of the heat exhaust of its cooling system constitutes the content of chapter 4. As a practical realization of the idea put forward in chapter 2, the design of the radiator for collecting and directing air heat exhaust is presented. The chapter showed that heat generated should be enough to maintain hydrogen regeneration of the MH reactor. While this important result is well justified, the choice of reactor is not clear. On the one hand, 1000 l MH reactor suggested for integration in the H2Smart system (chapter 5) is mentioned. On the other, experiments were made with the larger "semi-commercial" reactor. Moreover, air heating was used despite both reactors are designed for water cooling/heating. All these are quite misleading. Did the Thesis suggest air-cooled reactor concept despite the problem of water accumulation noted? Does the air-based system indeed "shows promising future", as concluded? And if yes, why this technology was not further explored?

Chapter 5 describes the design of the second prototype system with 1100 kW PEM-FC, called H2Smart. Unlike H2Bio system presented in chapter 2, new system includes autonomous hydrogen supply integrating electrolyzer with the water purification system. It also contains specially developed 1000 l MH reactor based on Ce-doped $LaNi_5$ alloy. The system description and demonstration of its function are convincing enough to be taken as the "proof-of-the-concept". However, analysis of the working regimes and flows looks rather brief, at least, much less detail is given than for the first H2Bio prototype.

Preliminary economic evaluation of the H2Smart system is given in chapter 6, for the test case of Batamai village. Careful assessment presented points out the advantage of the system, though the level of uncertainty is understandably high.

The Thesis submitted presents novel and practically important result, namely, the design of energy storage system integrating water-based hydrogen supply, hydrogen storage MH reactor, PEM FC with back up battery and internal heat transfer system. The viability of the integration concept and possibility to use it with load demand up to 1 kW are demonstrated and presented in a number of respectful journal and conference publications. I consider this result as significant, both as the new step in developing of energy storage technology and as the proof for high professional qualification of the author. With respect to the latter, I would like to acknowledge diverse skills demonstrated, including knowledge in physical chemistry, materials science, system engineering and simulations. No doubts that the author, Aliya Glagoleva, and her research outcome fit the criteria of the PhD degree of Skolkovo Institute of Science and Technology.

Alas, the composition and logic of the written presentation are not so bright. To me, the main weakness is the introductory chapter 1. First, combination of very general overview of energy storage technologies and very specific case of Batamai village is confusing. How does the author see her technology? As the general solution? But little practical alternatives of the similar scale are considered for comparison. As a specific solutions to Batamai-like village? Chapter 6 indeed proves the benefits of the proposed system in this case, but may be even more precise connections, like account for ambient temperature and humidity regimes and supply limitations, are crucial? Also, the review by Chen et al. [21] is used as the main source of overview of storage technology. Are there significant post-2009 achievements in this rapidly developing field? Second, the review of MH hydrogen storage technologies, though generally relevant, is poorly used in the main text. I think the author should be more precise in fitting introductory to the context of her research.

Presentation of the research part looks complete and justified, but suffers a bit from the lack of logical connections. Special attention should be paid for the problems pointed above for chapters 3 and 4. Other minor imperfections can be noted. And of course the text requires intent proofreading. There are multiple errors in referencing tables and figures, misprints and some language imperfections. The list of references should be properly formatted.

To avoid finishing with the criticism, I would like to stress once again that it addresses presentation aspect rather than the essence of the research work and outcomes.

Provisional Recommendation

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*