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REVIEW OF THE DOCTORAL THESIS
by Hamed Ghiasirad, MEng.
entitled: "Optimization of polygeneration systems using hydrogen as an energy carrier"
performed under the scientific supervision
of Professor Anna Skorek-Osikowska, PhD, DSc, Eng

1. Basis for the review

The formal basis for the review is the letter RIE-BD.512.37.2025 dated 03 October 2025 from the Chairperson of the Discipline Council of Environmental Engineering, Mining and Energy of the Silesian University of Technology, Prof. Krzysztof Labus, with a request to evaluate the dissertation of Mr Hamed Ghiasirad, MEng., and the contract for work UMC/3172/2025 for the performance of a review (doctoral degree) to the application number 2986/UMC/RIE0-1/2025, concluded between the Silesian University of Technology and the Reviewer, concerning the fulfilment by the above-mentioned dissertation of the conditions set out in Article 187 of the Act of 20 July 2018 – Law on Higher Education and Science.

2. Presentation of information about the doctoral dissertation

Title of the dissertation "Optimization of polygeneration systems using hydrogen as an energy carrier", in Polish "*Optymalizacja systemów poligeneracyjnych wykorzystujących wodór jako nośnik energii*", accurately summarizes the research topics taken up in the dissertation, focused on improving, both in economic and environmental terms, the technologies in which hydrogen produced in a solid-oxide electrolyzer can be successfully used for the production of liquid biofuels such as biomethanol, ammonia or aviation fuel. These improvements are supported by thermodynamic modelling, techno-economic analysis and cradle-to-grave life cycle assessment of eight energy system configurations, using hydrogen as an energy carrier, supporting the implementation of renewable energy and mitigating the risk arising from electricity-price volatility. I believe that the title is correctly formulated, and the research topics are a response to the need of the European Union for decarbonization of fuels while preserving energy security.

The doctoral thesis is written in the appropriate technical language in English and covers 135 pages. The dissertation consists of abstracts and key words, written in English and Polish languages, a table of contents, a nomenclature containing explanations of the abbreviation used, and eleven main chapters including: introduction with the current state of knowledge, motivation with the scope and hypotheses of the work, a part describing the subsystems using the hydrogen produced, and a presentation of five modelled polygeneration systems, with eight configurations, with the results of thermodynamic, technical-economic and environmental analyses, comparison of results and conclusions. At the end of the work there is an appendix and a correctly marked list of references covering 206 items. 91% of the literature is scientific articles, 85% of which were published in the last 10 years, and this emphasizes that the doctoral student has a very good knowledge of the current state of the art of the subject of the dissertation. In addition, it should be emphasized that the doctoral student is the first author of 10 and co-author of 2 of the cited references.

In the first chapter, the doctoral student presents the current energy policy and the state of current technologies supporting the production of hydrogen based on renewable energy sources in the context of achieving a reduction in greenhouse gas emissions by at least 55% by 2030 and a climate neutrality of the European Union by 2050. The doctoral student discusses, among other topics, the transformation of biomass into biofuel by means of anaerobic digestion or gasification, the production of hydrogen, with the indication of electrolysis powered by renewable energy as a "mature" technology, and the problems with its storage and application in various industrial configurations, and above all for the production of liquid fuels such as biomethanol, ammonia and jet biofuel, with particular emphasis on the impact of various systems on efficiency, levelized costs and life-cycle impacts.

The second chapter presents the motivation, scope and hypotheses of the dissertation. The main motivation of the doctoral student was to present on an industrial scale energy systems using hydrogen, produced on the basis of renewable energy, for the production of liquid biofuels, i.e. biomethanol, ammonia and jet biofuel, and to demonstrate that the integration of these systems allows to increase efficiency, reduce costs and avoid negative environmental impact by optimizing design of systems using hydrogen, biomass conversion, oxygen management, fuel synthesis and subsystems. The scope includes the design of five polygeneration systems with eight configurations and their evaluation from a thermodynamic, techno-economic assessment and environmental perspective. Correctly put forward hypotheses, they aim to determine which choice of hydrogen use/application is the most beneficial in terms of energy, economy and environment, in order to determine:

- increase the overall energy efficiency of the plant by using high-temperature electrolysis,
- improvement plant efficiency by coupling heat recovery from an oxygen turbine and LNG cold-energy recovery,
- management of heat recovery from oxygen generation between subsystems,
- increase system production capacity by integrating variants with compressed air and heat energy storage systems,
- improvement techno-economic indicators through the co-production of biofuels and natural gas,
- reduction of the environmental footprint by powering the polygeneration system with wind energy instead of the Polish electricity mix.

In the third chapter, the doctoral student presents a description and thermodynamic equations for all energy subsystems in the proposed polygeneration systems modelled in Aspen Plus, on the basis of which process optimization and detailed quantitative energy analysis were performed. These are the following subsystems: water electrolysis for alkaline and solid oxide electrolyzers, anaerobic digestion for biogas production, biogas purification by water-scrubbing, CO_2 dissolved by water, biomass gasification with steam and oxygen, ammonia synthesis, methanol synthesis, electricity and natural gas production with cooling recovery from LNG and oxygen turbine and carbon monoxide conversion with water vapor, cryogenic air separation unit to nitrogen and Oxygen. Compressed air and thermal energy storage systems, biojet fuel production using 4 stages, i.e. reverse water gas shift reactor, the Fischer-Tropsch reactor, distillation towers, and hydrocracking. Detailed data and assumptions for the calculations are collected in the appendix at the end of the work.

The fourth chapter is an introduction to the assumptions of the applied analyses: techno-economic and environmental. A techno-economic analysis was prepared to evaluate eight configurations in terms of payback time and levelized fuel cost in order to determine which of the proposed models is the most cost-effective and realistic to implement from an economic point of view. The Life Cycle Inventory has been developed based on data from reliable cited sources, simulations made in Aspen Plus and data from the Ecoinvent 3.11 database. The environmental analysis "from cradle to the grave" was carried out in accordance with a standardized procedure in SimaPro, with particular emphasis on obtaining the impacts of zero greenhouse gas emissions, climate change and the global warming potential, taking into account the 25 years of lifespan of the systems in Poland, based on electricity supply from wind energy and the Poland electricity mix. The life cycle analysis was carried out taking into account two different approaches, namely attributional and consequential LCA, which allow a different view of the analyses performed. Attributional LCA evaluates polygeneration systems from an engineering point of view with the identification of the most relevant environmental problems, the selection of materials and the gradual improvement of the tested systems. In contrast, consequential LCA is more focused on evaluating decisions, market responses, and policies to proposed models, so it takes a rather strategic approach to proposed changes over a longer lifespan. Both approaches complement each other and allow for a more complete environmental assessment of the proposed systems.

The next 5 chapters are a presentation of each of the five polygeneration systems with eight proposed configurations, their thermodynamic, techno-economic and environmental evaluation, i.e. attributional and consequential life cycle analysis, and a summary of the analyses carried out. The analyzed polygeneration systems, using green hydrogen as an energy carrier, with eight numbered configurations are as follows: biogas-to-methanol system, in which two variants are considered: 1) the base system, i.e. the integration of anaerobic digestion and biogenic CO_2 with green H_2 produced in an oxide electrolyzer powered by wind energy or from the Polish electricity mix, and 2) the improved system by the recovery of heat and cooling from the regasification of natural gas and oxygen turbine; 3) the methanol from syngas system, using gasification of biomass by steam and oxygen from an electrolyzer, and hydrogen from an electrolyzer, together with the production of natural gas; 4) the methanol from biomass gasification system, taking into account the recovery of waste heat from compressed air energy storage, power generation and natural gas production; ammonia production based on the so-called three green production pathways, i.e. 5) with the use of an air separation unit and an alkaline electrolyzer powered by energy from photovoltaic panels, 6) with the use of biomass gasification by steam and oxygen from an air separation unit powered by energy from photovoltaic panels and a co-current membrane-assisted water gas shift reactor for hydrogen production and capture of liquid CO_2, 7) the use of biomass gasification by steam and oxygen from an air separation unit powered by energy from photovoltaic panels and a counter-current membrane-assisted water gas shift reactor for hydrogen production and capture of liquid CO_2; 8) production of sustainable jet fuel from syngas, using biomass gasification by oxygen from an electrolyzer, processed into light hydrocarbons by Fischer–Tropsch synthesis, and natural gas combined with heat recovery from an oxygen turbine.

Chapter 10 compares the results from eight different configurations, on the basis of which the doctoral student selected the most promising configurations integrating the use of green hydrogen, oxygen, heat and electricity along with heat storage and recovery for the production of liquid biofuels. Thus, for biomethanol production, the most promising option is configuration 4, which uses biomass gasification taking into account the heat recovery from air compressed energy storage and natural gas production, due to the achievement of the highest energy efficiency of 95.27%, the largest fuel capacity of 8062 kg/h with the lowest environmental burdens, and one of the lowest prices. For ammonia production, the best solution is configuration 7, using biomass gasification by steam and oxygen from an air separation unit powered by energy from photovoltaic panels and a counter-current membrane-assisted water gas shift reactor for hydrogen production and capturing liquid CO_2, due to the highest energy efficiency of 54.64%, the lowest levelized cost of fuel ($513.28/tonne) and the lowest environmental burdens. For biojet fuel production, configuration 8, the production of sustainable jet fuel from syngas, using biomass gasification by oxygen from an electrolyzer, converted into light hydrocarbons by Fischer–Tropsch synthesis, and natural gas combined with heat recovery from an oxygen turbine, was the best solution.

The thesis concludes with a summary in which the doctoral student details 20 conclusions from the work performed, confirming that the integration of various systems powered by renewable energy in combination with the use of an electrolyzer and thermal-power coupling increases the efficiency of conversion, reduces levelized costs and lowers environmental impacts, and allows for the efficient production of liquid fuels. In my opinion, this part lacks a statement in which the doctoral student confirms that he has proven the hypotheses put forward in the thesis.

It is apparent that the title reflects the scope of the work, the hypotheses are understandable, and the calculations and analyses made seek to confirm the hypotheses. It should be mentioned that the performed analyses are comprehensive.

3. Evaluation of the doctoral dissertation

In my opinion, the dissertation is very interesting and original and conforms to current research trends. In addition, the results might be applied in the energy industry, which strives to achieve the decarbonization of fuels while preserving energy security. Therefore, I believe that the presented results are very important for green hydrogen technology development in Poland.

Moreover, integration with other processes optimized from a thermodynamic and environmental point of view will allow for the rapid development and implementation of these technologies.

The dissertation is easy to read. It is edited in correct manner. In addition, the technological diagrams are carefully made and described in detail, which allows for smooth familiarization with their content. The work arrangement in the research part is non-standard, due to the simultaneous presentation of the polygeneration systems discussed by the configurations and the results of thermodynamic, techno-economic and environmental assessment, with a short summary.

The main achievements of the doctoral student are:

- critical assessment of the national and global state of knowledge on the possibility of using hydrogen as an energy carrier in polygeneration systems for the production of liquid fuels, with particular emphasis on efficiency, cost and environmental assessment, prioritizing renewable energy, taking into account the constraints imposed by environmental legislation;
- mastering and using analytical tools in order to perform thermodynamic, techno-economic and environmental assessments, which proves the ability of the doctoral student to conduct analytical research, development of eight thermodynamic models for the considered configurations of polygeneration systems, which proves the deep substantive knowledge of the doctoral student,
- selection of reliable input data necessary to perform calculations supported by critical analysis,
- design of a functional unit and definition of boundary conditions for environmental assessment of the proposed configurations,
- identification of key performance indicators including overall energy efficiency, levelized cost of fuel, global warming potential and fossil resource depletion,
- performance of detailed thermodynamic, techno-economic and environmental analyses for eight configurations of five polygeneration systems using green hydrogen as an energy carrier,
- estimation of the risk associated with electricity-price volatility,
- a comprehensive approach to the optimization of the proposed polygeneration systems.

Please explain the following issues that I noted while reading the paper:

1. After performing the analyses of the use of hydrogen as an energy carrier integrated with energy systems, do you see the possibility of potentially implementing the most advantageous variant for the production of liquid fuels in Poland in the near future?
2. What were the criteria for selecting the biomass gasification process? Have you considered gasifying other organic waste, or the use of another conversion process?

3. When planning the implementation of anaerobic fermentation, did you take into account possible problems resulting from the complicated nature of the digestate?
4. Have you considered introducing an additional upgrading system for digestate? Do you plan to improve systems using liquefied CO_2? If so, how?
5. Do you plan to develop the polygeneration systems? If so, in which direction do you plan to pursue system integration?
6. Have you considered the implementation of the CCUS system?
7. In the dissertation, there was a note that you used experimental data collected by Prof. Bartela's team on waste heat recovery. Do you plan to conduct experimental research for any of the modelled variants?

While reading the dissertation, I noted a few editorial errors and a lack of consistency in the abbreviations of the nomenclature, mainly in the introduction part, which is less polished than the research part, e.g.:

1. P. 9. The nomenclature does not include many abbreviations used, especially from the introduction part, which initially made reading difficult, e.g.: AD, WGS, SAF, GWP, SOEC,FDP, LNG, CCUS, MSW, GHG, RNG, ETS, DS., AC, FT, ATR, PEM, TES, IRR,HEFA, ATJ, CEPC, UNIDO, TPC, AI, KIP and others.
2. P. 16. When describing solid oxide electrolysis, the doctoral student uses the terms SOEL and SOEC interchangeably, are they identical?
3. P. 18, point 1.6. The doctoral student uses the terms grey and green hydrogen, but there is no explanation of these terms.
4. P. 23 Table 1.2, first row, the abbreviation STC is used, which is not included in the description of solar thermal collector.
5. P. 34. Fig. 3.4 there is no description of P1 and P2 cited in the text.
6. P. 37. Equations 3.21 and 3.22. are incorrectly explained
7. P. 37 Table 3.2. Does the composition of the syngas a result of calculations or is it assumed in the work?
8. P. 39. Stream 88 is not depicted in Figure 3.10.
9. P. 40. Editorial error in the text: incorrectly marked equation 10.
10. P. 47. Is LCOF the same as LCOP?
11. P. 75. There is no explanation of the abbreviation NPV, which can be found in Fig. 6.6.
12. P. 129, p. 133. Lacs a full description of the cited papers no. 13 and 172.

I would like to emphasize that the above remarks are of a discussable nature, most of them are editorial errors and they do not diminish the scientific value of the reviewed work of the doctoral student, which I rate very well.

4. Summary

I declare that the reviewed doctoral dissertation meets the conditions and requirements set for doctoral dissertations set out in Article 187 of the Act of 20 July 2018 – Law on Higher Education and Science.

I evaluate the work very positively and in my opinion the doctoral dissertation "*Optimization of polygeneration systems using hydrogen as an energy carrier*" by Mr Hamed Ghiasirad, MEng., is an original solution to a scientific problem. Mr Hamed Ghiasirad has shown high scientific maturity by formulating hypotheses, determining the scope of work, performing calculations and their analysis, and correctly formulating the final conclusions confirming the hypotheses. I believe that Mr Hamed Ghiasirad has shown that he has general theoretical and practical knowledge in the scientific discipline of environmental engineering, mining and energy, as well as the ability to conduct scientific work independently. **In conclusion, I bring forward the motion to the Discipline Council of Environmental Engineering, Mining and Energy of the Silesian University of Technology to admit Mr Hamed Ghiasirad, MEng., to the further stages of the procedure for a doctoral degree.**

I also request that the doctoral dissertation of Mr Hamed Ghiasirad, MEng., be recognized due to its originality, wide scope and comprehensive approach to research, taking into account technical, economic and environmental aspects and the prospect of developing polygeneration systems using hydrogen, generated using renewable energy sources, for the production of liquid biofuels and natural gas.

Podpisała Małgorzata Wilk