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Czestochowa, 21 November 2025

REVIEW

of the doctoral dissertation of Mr. Hamed Ghiasirad, M.Sc. Eng.

entitled

„Optimization of polygeneration systems using hydrogen as an energy carrier"

prepared at the Faculty of Environmental Engineering and Energy of the Silesian University of Technology in Gliwice,

carried out under the supervision of Professor Anna Skorek-Osikowska

The review was prepared at the request of the Chairman of the Scientific Discipline Council for Environmental Engineering, Mining and Energy of the Silesian University of Technology in Gliwice

Professor Krzysztof Labus, dated 25 September 2025

1. Formal basis for preparing the review

The review was prepared in accordance with Contract No. UMC/3174/2025, dated 8 October 2025, concluded between the Silesian University of Technology in Gliwice and its author.

2. Information regarding education and the course of the scientific and professional career of Mr Hamed Ghiasirad, M.Sc. Eng.

The Doctoral Candidate obtained his engineering degree in 2016 at Qazvin Azad University in Qazvin (Iran) and his master's degree in 2019 at Sahand University of Technology in Tabriz (Iran). To the best of my knowledge, Mr Hamed Ghiasirad, M.Sc. The applicant, who is an engineer, has not previously applied for a doctoral degree. Between 2022 and 2025, he was a participant in the Doctoral School of the Silesian University of Technology, focusing on Environmental Engineering, Mining, and Energy. The Candidate's scientific and professional achievements in previous years developed as follows:

- Research Asistant of Niroo Research Institute, Tehran, Iran (2019-2020)
- R&D engineer in the Ashja Battery Company, Ardabil, Iran (3 months in 2020)
- Teaching Assistant of Aspen Plus, Silesian University of Technology (4 months 2022)
- Teaching Assistant, Energy Storage, Silesian University of Technology (2023)
- Teaching Assistant, Alternative Energy Sources, Silesian University of Technology (2024)
- 2-month research internship in 2023 w Karlstad University, Life cycle assessment of a biogas-to-methanol plan, Karlstad, Sweden
- 3-month research internship in 2024 w Forschungszentrum Jülich, Life cycle assessment of Fischer-Tropsch reactor to produce sustainable aviation fuels. Jülich, Germany
- project executor in the grant to start scientific activity in a new research topic, Silesian University of Technology, A solar biomass driven power/desalination unit including an

experimental addition of nanofluid to the main flow of collector: Thermodynamic modeling, (32/014/SDU/10-22-37)

- project executor in BKM grant, Silesian University of Technology, Techno-economic and Life Cycle Assessment of Biofuel Production Plants (RIE5/2024 08/050/BKM_24/0)
- participation in Summer School 2024, COST Action. TEA for CCUS/NETs and process modeling, Technical University in Prague, Czech Republic.
- participation in Summer School 2023, COST Action. Understanding synergies and differences of TEA of CCUS and NETs. NTNU, Norway.
- participation in Workshop on Smart Energy Systems, University of Tehran, 2020.
- 3 times -The best Ph.D. student at Silesian University of Technology, Poland (2022-2024)
- Award for Highly Scored Publications and Projects at SUT, Poland (2024)
- Outstanding researcher in mid-term evaluation, SUT (2023).

3. Subject matter of the doctoral dissertation

The subject matter of the doctoral dissertation by M.Sc. Eng. Hamed Ghiasirad addresses the issue of optimising polygeneration systems that utilise hydrogen as an energy carrier, considering efficiency, cost, and environmental parameters. The dissertation assumes that hydrogen, being a valuable energy source and at the same time an intermediate product of thermochemical transformations, is a key common element of the examined technologies based on a solid oxide electrolyser cell (SOEC), leading to the production of various biofuels. The thesis addresses issues related to improving conversion efficiency, reducing the levelized cost of fuel, and lowering the potential environmental impact of the "cradle-to-gate" type through the application of a process solution using hydrogen with targeted separations, including thermal–electrical integration. Undertaking this type of subject matter fits into current research directions, whose overarching goal is environmental protection and concern for the quality of life of future generations. The pursuit of optimising energy processes, waste neutralisation, and their energetic conversion is consistent with the concept of sustainable development. It should be emphasised that the conversion of renewable electricity and biogenic carbon based on polygeneration systems, leading to the synthesis of various fuels, requires the integration of electrolysis, heat recovery, and simultaneous management of oxygen and carbon. The research problems addressed in the dissertation, concerning the possibilities of obtaining "drop-in" type energy carriers in the form of liquid and gaseous fuels chemically identical to their counterparts derived from fossil fuels, are closely related to the decarbonisation process, and the ultimate effect of the proposed solutions is the achievement of energy independence. In line with the "zero waste" concept, i.e., the pursuit of optimising energy processes in the context of reducing by-products, the Candidate assessed strategic indicators of the optimisation of the polygeneration process based on hydrogen utilisation, determining the total energy efficiency, the levelised cost of fuel (LCOF), the global warming potential (GWP), and the fossil depletion potential (FDP).

The choice of dissertation topic is exciting and timely. Based on Aspen Plus 12.1 software, the Author developed unified analytical frameworks, including thermodynamic models, together with a techno-economic assessment used, among other things, for analysing the physical and chemical properties of the investigated systems. Furthermore, using SimaPro 10.2 software, the Candidate conducted attributional and consequential life cycle analyses for eight different configurations. A multidirectional approach to optimising polygeneration systems based on hydrogen as an energy carrier represents a significant advancement in the current state of knowledge in this field.

It is worth emphasising not only the scientific nature of the dissertation but also its future application potential. The issues explored in the thesis pertain to highly topical research areas, such as hydrogen energy. In cases where environmental criteria outweigh economic ones, the prioritisation of biofuels constitutes a valuable energy carrier. It is highlighted that the use of hydrogen in polygeneration systems can bring, for an industrial plant implementing the proposed technological solution, depending on the examined configuration, additional environmental and economic benefits.

4. Characteristics of the doctoral dissertation

The doctoral dissertation submitted for review by M.Sc. Eng. Hamed Ghiasirad consists of 135 pages of typescript and includes references to 64 figures and 37 tables (including 14 placed in the Appendix). The dissertation comprises a summary (in both English and Polish), a table of contents, a list of abbreviations and symbols, a theoretical section divided into 8 subsections, a chapter dedicated to the objectives, scope and hypotheses of the work, an experimental section divided into 7 chapters, a summary in the form of a comparison of results and conclusions, an appendix, and a bibliography.

Chapter 1. "Introduction", is divided into eight subsections and provides the scientific background of the work. In the introductory part of this chapter, the Doctoral Candidate broadly outlined the issue concerning the need to reduce greenhouse gas emissions, which pose a threat to sustainable development, while referring to possible EU climate mitigation strategies, particularly in relation to the implementation of hydrogen energy. The Candidate emphasised that the production and use of green hydrogen are the most important systemic levers for achieving the EU's climate targets for 2030. It should be noted that, based on the literature review in this chapter, the Candidate specified the essential scientific problems, thereby indicating the main research directions of the dissertation, which were subsequently confirmed in the subsequent chapters.

In the first subsection 1.1. of the theoretical part, titled "Renewable Energy," the Candidate characterised renewable energy sources, taking into account the benefits of their use for both the European Union and Poland.

In subsection 1.2. titled "Biomass Conversion," the Candidate described the main biomass conversion technologies, i.e., anaerobic digestion and biomass gasification, highlighting the environmental and energy-related benefits of their implementation. Regarding the anaerobic digestion process, the Candidate pointed out the possibility of

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obtaining energy and raw materials from biomass, which aligns with the concept of a circular economy. The Candidate noted that biomass gasification technology is considered a beneficial method of converting waste into hydrogen with high energy value. Referring to the concept of a global hydrogen economy, he emphasised the role of hydrogen in decarbonising the energy, transport, and chemical sectors.

Based on the literature review presented in subsections 1.3. "Hydrogen Production", and 1.4. "Hydrogen Production Using Electrolysis Cells", the Doctoral Candidate indirectly identified a research gap, emphasising that achieving net-zero emissions is attainable through the use of an electrolyser powered by renewable energy and bioenergy combined with Carbon Capture and Storage (CCS). The Candidate further recognised the electrolysis process based on renewable energy sources as technologically mature, highlighting that such a solution is characterised by stable fuel production and flexible operation in terms of absorbing variable wind and solar energy. However, this depends on the scale of hydrogen production, which is conditioned by the development of renewable energy sources. The Candidate provided a detailed description of electrolysis technologies for hydrogen production, forming the basis of polygeneration pathways, noting that solid oxide electrolysis remains in the pre-commercial (early pilot) phase. Nevertheless, when operating at high temperatures with steam, it achieves the highest efficiency compared to alkaline electrolysis or proton-exchange membrane electrolysis.

In subsection 1.5. titled "Hydrogen Storage Challenges," the Doctoral Candidate addressed the limitations associated with hydrogen storage and the safety aspects related to hydrogen logistics, indicating that the optimisation of this process focuses on "power-to-X" and "biomass-to-X" polygeneration pathways in which hydrogen is immediately used for the production of fuels/chemical substances. This approach reduces systemic risk while enabling deep decarbonization. The Candidate emphasised that this solution is more practical and safer in terms of fuel storage/logistics. He noted that the conversion of hydrogen (from renewable electricity or syngas/biogas derived from biomass) into bioproducts makes it possible to obtain energy carriers that are denser, can be stored under milder conditions, and are compatible with existing infrastructure.

In subsection 1.6. "Hydrogen Applications," the Candidate analysed potential uses of hydrogen, highlighting that hydrogen produced via the "power-to-X" and "biomass-to-X" pathways may be applied in refining and hydrogenation processes, fertiliser/ammonia production, and methanol synthesis methanol being a key intermediate in chemical production and an emerging transport fuel. Furthermore, he emphasised its application in transport and aviation, chemical feedstock production, crude steel manufacturing, energy storage, and biogas upgrading.

Next, in the subpoints of subsection 1.6 namely 1.6.1. "Power and Biomass to Methane," 1.6.2. "Power and Biomass to Methanol," 1.6.3. "Power and Biomass to Ammonia," and 1.6.4 "Power and Biomass to Jet Fuel" the Doctoral Candidate discussed technologies directly related to the subject of the dissertation, providing a detailed characterization of each, including the required process conditions.

In Chapter 1.7. "Summary", the Doctoral Candidate highlighted the novelty aspect of the dissertation, indicating how promising the Power-and-Biomass-to-Liquid (PBtL) process is as a technological solution for producing liquid biofuels such as biomethanol, ammonia, or jet fuel, particularly in the context of utilising the existing global logistics infrastructure for chemicals and liquid fuels.

In the final part of the literature review concerning the subject of the dissertation, i.e., in section 1.8. "State of the Art," and the corresponding subsections 1.8.1.–1.8.4. the Candidate presented a detailed characterization of selected hydrogen technologies, demonstrating a holistic approach to the scientific problem described, including installation efficiency, levelized costs, life-cycle impacts, and techno-economic and environmental analyses of the examined solutions.

In subsection 1.8.1. "State of the Art in Biomethanol Production," he conducted a critical review of the literature on biomethanol production using hydrogen, indicating how the integration of H_2 affects the efficiency, costs, and environmental performance of biofuel systems. Based on this, he outlined technological advancements and identified research gaps related to the considered technology. The Candidate noted that previous studies conducted by researchers focused on power-to-methanol installations using electrolysis cells. Only a few researchers have considered methanol production systems that integrate hydrogen obtained via water electrolysis with CO_2 separated from gas installations, or the technological, environmental, and economic aspects of methanol production through CO_2 hydrogenation using hydrogen obtained from proton-exchange membrane electrolysis and CO_2 originating from natural gas deposits. The Candidate then discussed methanol production from biogas, emphasizing the cost-effectiveness and environmental friendliness of this technology. They analyzed the possibility of using a high-temperature electrolyzer for its production, along with various options for integrating a methanol-generation system. He conducted a detailed analysis of the data regarding the overall efficiency of the considered polygeneration systems.

In subsection 1.8.2. "State of the Art in Energy Storage Integrated Hydrogen Utilization," hybrid hydrogen and energy storage systems integrated with high-temperature electrolysis were described. The Doctoral Candidate identified solutions that combine waste-heat utilization and storage such as installations using hydrogen as an energy carrier and compressed-air energy storage (CAES) systems as efficient in improving process performance, cost-effectiveness, and reducing greenhouse gas emissions.

The Candidate emphasized that hydrogen production is feasible within a biomethanol-production system integrated with energy storage by means of a high-temperature electrolyzer. High-temperature processes, such as gasification or fuel synthesis, can be integrated with this type of electrolyzer, as the heat generated during these processes can be utilized to reduce the electrolyzer's energy demand. He pointed out that high-temperature electrolyzers have strong development potential and the capability to cooperate with various types of energy installations. Based on a critical review of the literature, the Candidate underlined that the hybridization of energy-storage systems is

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consistent with the principles of the circular economy and is becoming an increasingly common approach for maximizing the energy potential of available energy carriers.

In subsection 1.8.3. "State of the Art in Ammonia Production," the Candidate conducted a critical review of the technological, economic, and environmental aspects of green and biomass-based ammonia production technologies to optimize polygeneration systems that use hydrogen as an energy carrier. Against this background, the Candidate identified development goals for the considered ammonia-production technologies and noted the design limitations of the examined solutions. He emphasized that the increasing global demand for ammonia resulting from its applications in energy storage and the decarbonization of hydrogen energy systems underscores the need to transition from traditional production processes to more sustainable and environmentally friendly alternatives. In this context, the Candidate pointed to renewable energy-based methods of producing green hydrogen for ammonia synthesis units, namely water electrolysis and biomass gasification, powered mainly by solar and wind energy.

Based on a techno-economic analysis and life-cycle assessment of hydrogen-energy systems, the Candidate indicated that a promising solution and potential alternative to green ammonia are ammonia synthesis units equipped with a proton exchange membrane electrolyzer, noting that the cost of producing ammonia via electrolysis technology strongly depends on the price of renewable energy.

In subsection 1.8.4. "State of the Art in Biojet Fuel Production," an overview of technologies for producing aviation biofuel was presented, considering subsystem integration, conversion efficiency, costs, and life-cycle aspects. The Doctoral Candidate emphasized key design considerations and highlighted existing gaps in the development of the analyzed technological solutions, which form the basis for optimizing the course of the polygeneration process using hydrogen to produce sustainable aviation fuel (SAF). The analysis covered solutions based, among others, on the power-and-biomass-to-liquid (PBtL) technology, which combines biomass gasification, Fischer–Tropsch synthesis, and electrolysis.

Summarizing the information contained in the literature section of the dissertation, the Candidate identified a research gap, stating that from a thermodynamic perspective, integrating gasification, high-temperature electrolysis, and synthesis loops requires expanding current knowledge, with a focus on improving efficiency through the cogeneration of liquid and gaseous fuels. As he emphasized, new systems should focus on utilizing heat, oxygen, and CO_2. Existing techno-economic studies assume stable operation and overlook the valuation of flexibility and revenue stacking. Life-cycle assessments, meanwhile, are inconsistent in terms of system boundaries and approaches to biomass sustainability. Therefore, these issues constitute an essential aspect of the research presented in the doctoral dissertation by M.Sc. Eng. Hamed Ghiasirad represents the novel contribution of the work.

In my opinion, the theoretical part of the dissertation presents a concise and well-structured elaboration of issues closely related to the work's aim, the hypotheses formulated, and the proposed research scope. Through a critical review of the literature, the Doctoral Candidate identified research problems that have not yet been fully recognized and for which the existing body of knowledge requires expansion. The theoretical part of the dissertation is supported by 82 literature references, which demonstrates the Candidate's strong understanding and thorough recognition of the topic.

In Chapter 2. of the dissertation, titled "Motivation and Scope of the Thesis," the Doctoral Candidate presented the motivation for undertaking the chosen research topic. He also specified the scope of the work and the research hypotheses. The motivation is based on the assumption that "at plant scale, coordinated use of hydrogen, oxygen, heat, and power, together with surplus energy storage and waste heat-recovery options, can unlock system-level advantages unreachable by analysis of single components alone." Summarizing this premise, it was stated that "it is possible to increase efficiency, reduce costs, and avoid environmental footprints by design optimization of hydrogen utilization, biomass conversion, oxygen management, fuel synthesis, and utility subsystems."

Furthermore, the Candidate formulated the scope of the work, outlining the chronology of the research stages and indicating the interrelations and dependencies between them, which includes:

- Building steady-state models for biomass digestion/gasification, alkaline and solid-oxide electrolysis, water–gas shift, CO_2 capture/recycle, methanol and ammonia synthesis, jetfuel upgrading, and distillations.
- Representation of oxy-fuel gas turbines for power generation, LNG regasification for heat recovery, and energy recovery from compressed-air/thermal energy storage (CAES/TES).
- Thermodynamic analysis, heat integration, and energy efficiency calculations.
- Levelized cost metrics and cradle-to-gate life-cycle indicators for wind-powered systems and benchmarking with Poland electricity mix.
- Design optimization and sensitivity analysis according to efficiency, cost, and emissions. robustness to electricity price and performance variability.

The Doctoral Candidate indicated that the aim of the work, among the five newly proposed polygeneration systems, is to identify the best solution in terms of hydrogen utilization.

The dissertation presents six research hypotheses, for the verification of which appropriate studies were conducted, namely:

- It is possible to increase overall energy efficiency of plants by adopting high-temperature electrolysis.
- It is possible to improve plant performance by coupling oxy-fuel gas turbine and LNG cold-energy recovery.
- It is possible to manage oxygen utilization among subsystems.
- It is possible to raise production capacity by integrating CAES/TES energy storage systems.

- It is possible to improve techno-economic indicators through co-production of biofuels and natural gas.
- It is possible to decrease environmental footprints by powering the plant with wind Energy instead of Poland electricity mix.

The research methods described by the Doctoral Candidate in Chapter 3. "Process Modeling of Subsystems for Hydrogen Utilization," made it possible to verify the research hypotheses formulated in the dissertation and are appropriate for the intended aim of the doctoral work. The Author presented a general characterization of the considered processes and their respective units, such as water electrolysis, anaerobic digestion unit, biogas upgrading unit, biomass gasification, ammonia synthesis subsystem, methanol synthesis unit, power and natural gas production subsystem, air separation unit, compressed-air and thermal energy storage systems, and the biojet fuel production system. In this chapter, the Candidate included models of all hydrogen-utilization subsystems, which form the basis for optimizing polygeneration systems.

It is worth emphasizing that the verified models and the assumptions presented constitute a quantitative foundation for evaluating the dissertation's hypotheses regarding the impact of integration on the efficiency, costs, and environmental performance of the analyzed technological solutions. Furthermore, the methodology suitable for the energy analysis of the studied polygeneration processes and the analytical studies i.e., essential equations, modeling techniques, and computational procedures was discussed comprehensively, along with the precise assumptions necessary to carry out this analysis clearly and accurately. The information contained in this chapter was supplemented with data provided in the Appendix.

In Chapter 4. "Techno-Economic and Life Cycle Assessment Methodology," the Doctoral Candidate defined the framework for the techno-economic and life-cycle assessment, which rigorously tests the hypotheses concerning the optimization of hydrogen-powered polygeneration systems. The establishment of system boundaries, data sets, cost-scaling approaches, performance indicators, and scenario design determines the process models as transparent, making the decision indicators reproducible and linking integration aspects with quantitatively defined efficiency values, costs, and environmental analyses.

In subsection 4.1. "Techno-Economic Analysis" the Doctoral Candidate noted that the techno-economic assessment would involve comparing eight configurations from two perspectives: payback time and the levelized cost of fuel. These two useful functions are essential for determining optimal operating points and facilitating the design of biofuel plants. Production costs were adjusted using the Chemical Engineering Plant Cost Index (CEPCI), referring to 2023 data. Forecasts were based on discounting techniques consistent with the standards of the United Nations Industrial Development Organization (UNIDO) and rely on calculating the net present value (NPV). As the Candidate pointed out, this approach offers a comprehensive and reliable framework for evaluating the project's economic performance over time.

The Candidate emphasized that while NPV reveals whether an investment is financially viable on a broader scale, LCOP shows how cost-effective the system is at the unit level and can help determine the break-even threshold. Together, NPV and LCOP provide insight into both high-level investment performance and detailed cost competitiveness, enabling sound economic decision-making.

In subsection 4.2. "Life Cycle Assessment", and specifically in subsections 4.2.1. "Consequential LCA using Impact 2002+" and 4.2.2. "Attributional LCA using ReCipE 2016," the Doctoral Candidate presented the conditions for conducting a comprehensive environmental life-cycle assessment of the analyzed hydrogen-utilization systems for biofuel production, with particular emphasis on structural optimization of the systems to achieve near-zero greenhouse gas (GHG) emissions related to climate change or global warming potential (GWP) impact categories.

The Candidate defined the functional unit as 1 kg of biofuel or 1 kg of input biomass, providing a consistent basis for comparing the environmental impacts of the considered solutions. He emphasized that the work focuses on a Cradle-to-Gate life-cycle assessment (LCA), primarily considering the process itself. Meanwhile, life-cycle inventory (LCI) data are collected from verified sources, namely Aspen Plus process simulation models and the Ecoinvent v3.11 database.

According to the Candidate, the study applies a long-term Consequential Life Cycle Assessment (CLCA) approach using SimaPro v10.2. In practice, the processes are paired with the Ecoinvent system "substitution, consequential, long-term," so that marginal links and substitutions are applied in accordance with ISO guidelines on goal and scope definition and ILCD recommendations for decision-oriented assessments aimed at avoiding harmful products and promoting value-added alternatives. SimaPro provides direct access to this consequential model and the current Ecoinvent v3.11 dataset.

For impact assessment, the Candidate selected IMPACT 2002+, a mature hybrid method that combines midpoint indicators with four damage/endpoint categories human health, ecosystem quality, climate change, and resource use. It is implemented natively in SimaPro, supporting decision-oriented synthesis. To enable a transparent comparison of LCA allocation methods, the Candidate first applied the consequential LCA (CLCA) with IMPACT 2002+, which accounts for long-term, market-mediated consequences of the decision context. Accordingly, IMPACT 2002+ was recognized as an appropriate and widely used LCIA method, combining 14 midpoint categories with four damage endpoints.

This section further complements CLCA by presenting an attributional LCA (ALCA), which characterizes average product allocation within current technology and supply structures, using the state-of-the-art ReCipE 2016 Midpoint (H) method for impact assessment in SimaPro. ReCipE 2016 offers updated and harmonized characterization factors across a comprehensive set of midpoint impact categories, providing enhanced modeling capabilities.

In subsection 4.3. "Overall key performance indicators", the Doctoral Candidate defined the key indicators essential for achieving the intended research scope, including:

energy efficiency (η_{en}), levelized cost of fuel (LCOF), global warming potential (GWP), and fossil depletion potential (FDP). The Candidate noted that fuel production capacity defines the plant-scale mass/energy balance and determines plant sizing. It enables the comparison of configurations on an everyday functional basis and allows verification of whether optimal designs still meet the target fuel production levels. This is a fundamental performance indicator in the proposed hydrogen-utilization systems. It quantitatively defines the steady rate of saleable fuel production under specified operating conditions. It determines whether a plant is considered small, medium, or significant within the context of a given industry. Beyond simple throughput, production capacity shapes design choices, cost structure, and environmental performance.

The presented description of the research methodology is comprehensive, indicates the proper sequencing of the conducted studies, corresponds to the adopted scope of work, and illuminates the research issues discussed in the results section.

In the following five chapters of the dissertation, the Doctoral Candidate analyzed hydrogen-based polygeneration systems, selecting those that prioritize liquid energy carriers in sectors difficult to electrify, while simultaneously leveraging the deep process integration enabled by electrolytic hydrogen and oxygen. As the Candidate states, while power-to-gas (PtG) technology is technologically mature for long-term energy storage, it is mainly limited to gaseous energy services. In contrast, power-and-biomass/biogas-to-liquids technologies provide ready-to-use products that are compatible with existing logistics and combustion infrastructure.

All chapters 5–9 are structured in the same manner: they include an introduction outlining the essence of the analyzed system, a section presenting thermodynamic results, techno-economic results, environmental consequences, attributional environmental results, and a summary of the conducted studies.

In Chapter 5. titled "Power and biogas to methanol", the Doctoral Candidate analyzed two biogas-to-methanol installations that integrate anaerobic digestion and biogenic CO_2 with green H_2 to produce biomethanol. The enhanced case integrates power and natural gas production with the baseline configuration.

In Chapter 6. titled "Biomass-to-methanol system using gasification", the Candidate analyzed a biomass-to-methanol system with power and natural gas production, combining oxygen-blown gasification with a solid oxide electrolyzer to increase biomethanol and natural gas yields.

In Chapter 7. titled "Biomass-to-methanol with energy storage", the Candidate evaluated the integration of a biomass-to-methanol system with energy storage systems that recover waste heat from CAES/TES units for the biomethanol plant to increase energy efficiency.

In Chapter 8. titled "Ammonia production plants", the Candidate evaluated three cases of biomass-to-ammonia installations in which a Haber–Bosch reactor is used while simultaneously supplying green hydrogen and utilizing O_2 from the electrolyzer with CO_2 capture to produce an easily liquefiable hydrogen carrier suitable for seasonal storage.

In Chapter 9. titled "Biojet fuel production system", the Candidate analyzed a biomass-to-aviation-fuel system that converts biogenic syngas into a sustainable aviation fuel (SAF) intended for long-distance transport requiring high volumetric energy density, while simultaneously producing natural gas.

It is worth emphasizing that both the research methodology and the research stages are coherent and were defined by the Doctoral Candidate correctly and in accordance with the intended objective of the dissertation. The research results are presented logically, and the tables, figures, and mathematical formulas integral parts of the dissertation and also included in the appendix facilitate their proper interpretation and evaluation.

In Chapter 10. titled "Comparison of results", the Candidate consolidated and compared, in the form of a comprehensive assessment aimed at identifying the best hydrogen-utilization configuration, the results of eight renewable-energy-based pathways: biogas-to-methanol (baseline and enhanced), biomass-to-methanol (with and without LNG/energy-storage systems), power-to-ammonia, biomass-to-ammonia (CO/CC WGS), and biojet fuel via FT synthesis. The Candidate demonstrated that the outcome of this comparative assessment is a justified selection of the best system for hydrogen utilization and the production of biofuels/chemicals, as well as a set of general design guidelines for process optimization.

Chapter 11. titled "Conclusions", comprises two pages of text. Based on the obtained research results, the Candidate proved the validity of the formulated research hypotheses, presenting twenty highly detailed conclusions. Additionally, at the beginning of the chapter, the Candidate highlighted the novelty aspects of the research, stating that the dissertation integrates thermodynamic modeling with techno-economic assessment and life-cycle analysis across eight innovative configurations: biogas-to-methanol processing, two biomass-to-methanol configurations—including systems with LNG-based heat recovery and energy storage—three ammonia production scenarios, and biojet fuel production.

From an editorial standpoint, the dissertation raises no concerns. In terms of writing style, it is linguistically appropriate and consistent, with any minor errors or inaccuracies being negligible and not affecting the overall evaluation of the work.

5. General substantive assessment of the doctoral dissertation

There is a strong correlation between the analyses carried out delving into the essence of the polygeneration process based on the considered renewable-energy systems and their practical application, which, in my opinion, constitutes a significant contribution of the Doctoral Candidate to the development of science. Mr. Hamed Ghiasirad, M.Sc. Eng. is a researcher capable of planning experiments, conducting the intended studies, and correctly analysing research results, presenting them in a highly academic manner. It is particularly worth emphasizing that the Doctoral Candidate successfully achieved the dissertation's objective by confirming the formulated research hypotheses.

The conducted studies and the obtained results contributed to a deeper understanding of the mechanisms underlying the polygeneration process, particularly in the context of using hydrogen as an energy carrier. The Doctoral Candidate developed and evaluated hydrogen-based polygeneration configurations for the production of liquid biofuels, with particular emphasis on biomethanol, ammonia, and biojet fuel. He accomplished the stated aim of the dissertation, which was to identify an integration strategy that effectively increases efficiency, reduces costs, and minimizes environmental impact in hydrogen-powered polygeneration systems.

Moreover, it is worth noting that only a limited number of studies compare LCA results under varying allocation strategies and electricity sources. The Doctoral Candidate pointed to the need to specify the particular requirements of a given pathway, including heat recovery from fuel synthesis units, surplus biofuel production, and recycling of residual gases in PBtL systems, as well as the need for a harmonized comparison of energy, techno-economic, and LCA results with similar works. Accordingly, the coherent research program presented by the Doctoral Candidate aimed to integrate CAES/TES energy-storage systems, waste-heat recovery, and synthesis units, and to report harmonized KPIs concerning fuel yield, energy efficiency, LCOF, and life-cycle impacts to optimize hydrogen-based polygeneration systems.

The systems "Power and biogas to methanol," "Biomass-to-methanol system using gasification," "Biomass-to-methanol with energy storage," "Ammonia production plants," and "Biojet fuel production system" incorporate the use of woody biomass or sewage sludge, as well as baseline and operational functionality supported by energy storage. These systems were selected by the Doctoral Candidate to demonstrate, in comparative scenarios, how hydrogen-based polygeneration units can increase efficiency, reduce the levelized cost of fuel (LCOF), and decrease LCA impacts. It was shown that the chemical storage of liquid biofuels is easier and safer than compressed/cryogenic storage of H_2 gas, that high-temperature electrolysis (SOEC) enables synergistic heat and power integration, supplies O_2 to eliminate air separation, and delivers H_2 for the production of biomethanol, ammonia, and biojet fuel collectively increasing system performance. Moreover, the Doctoral Candidate demonstrated that:

- ✓ The ammonia cases highlight that the least-cost PtA with alkaline electrolyzer is not the most energy-efficient, while biomass-to-ammonia with membrane WGS maximizes efficiency.
- ✓ Counter-current WGS membrane reactors consistently outperform co-current designs on H_2 recovery and overall efficiency. LNG cold-energy recovery and oxy-fuel gas turbines lower net power demand.
- ✓ Cogeneration of biomethanol and natural gas with O_2/CO_2 management shortens payback time and increases robustness to electricity-price volatility compared with single-product plants.
- ✓ Electrolyzer and fuel-synthesis units dominate CAPEX. Therefore, electricity price, sourcing, and electrolyzer temperature/current density are first-order determinants of levelized cost across all pathways.
- ✓ Raising WGSR conversion, methanol reactor temperature, or SOEC size increases conversion efficiency but can lift power demand or CO2 emissions.
- ✓ Wind energy significantly reduces cradle-to-gate GHG emissions and fossil resource depletion relative to the Poland electricity mix. process intensification (oxy-gas turbine with CO_2 injection, LNG cold-energy recovery) further improves footprints and can reduce site water use.
- ✓ SOEC is preferred when high-temperature integration is feasible.
- ✓ A counter-current WGS membrane reactor is selected for ammonia production.
- ✓ LNG cold-energy recovery and oxy-combustion are included when grid relief and flue-gas recycling are priorities.
- ✓ Cogeneration of natural gas and biofuels is advantageous under high or volatile electricity prices.
- ✓ Renewable energy is chosen when environmental sustainability is prioritized.

- ✓ Compressed air and thermal energy storage modules convert transient waste heat into steady biomethanol product, reducing grid variability and efficiency enhancement.
- ✓ Design optimization workflow yields decision-ready trade-off maps for efficiency, cost, and emissions based on heat-power integration, electrolyzer placement/sizing, and subsystems coupling with TEA-LCA feedback.
- ✓ The improved BtM with CAES/TES is the overall optimum for hydrogen utilization, highest efficiency (95%), competitive cost (602 $/tonne), and the lowest GWP (0.135 $kgCO_2eq/kgFuel$), validating the thesis on high-temperature, deeply integrated heat recovery around SOEC, gasification, and LNG.
- ✓ For ammonia, the BtA route with counter-current membrane WGS is preferred, acceptable efficiency (54.6%), the lowest cost among all plants (513 $/tonne), and near-zero GHG intensity (0.175 $kgCO_2eq/kgFuel$) due to superior H_2/O_2 and N_2 management.
- ✓ The biojet pathway remains strategically important for hard-to-electrify aviation (efficiency 56%, cost 1893 $/tonne, GWP 0.464 kgCO2eq/kgFuel).
- ✓ Optimal hydrogen utilization emphasizes O_2/steam gasification, high-temperature SOEC (with ALE as a cost lever), counter-current WGS membranes, integrated heat recovery between LNG–GT and CAES/TES and coordinated O_2/CO_2 utilization across subsystems.
- ✓ The Polish energy mix is the more economically viable option than wind turbines. However, wind energy outperforms Poland's electricity mix in most of the environmental indicators. The reductions are substantial, particularly concerning climate change and fossil resource scarcity, demonstrating the critical role of renewable energy in achieving carbon neutrality and mitigating environmental degradation.

It must be stated that the comparison of the eight renewable-energy-based pathways directly verifies the proposed research hypotheses, and that the coordinated utilization of

H_2, O_2, heat, and electricity together with storage and waste-heat recovery may prove more advantageous in terms of process efficiency, economics, and environmental performance than units operating in isolation.

Moreover, based on the obtained research results and literature data, the Doctoral Candidate highlighted that as variable renewable energy increasingly penetrates energy systems, the process industry requires solutions that enable the conversion of irregular energy into value-added, storable products while minimizing costs and environmental footprint. Hydrogen energy plays a crucial role in this transition, as it enables deep process integration encompassing electrolysis, biomass conversion, synthesis, and utilities. However, most previous assessments consider these units in isolation rather than as integrated polygeneration systems.

The Doctoral Candidate emphasized that while power-to-gas (PtG) technology is technologically mature for long-term storage, it is mainly limited to gaseous energy services. In contrast, power-and-biomass-to-liquid (PBtL) technology provides end-use compatible products that fit seamlessly into existing logistics and combustion infrastructure.

In summary, the dissertation represents an original solution to a scientific problem, and the Doctoral Candidate has acquired the theoretical knowledge necessary to carry out the planned research task, which is of considerable cognitive and practical significance. It is worth emphasizing that M.Sc. Eng. Hamed Ghiasirad conducted a wide range of studies that required the application of various modeling and analytical tools, demonstrating the Doctoral Candidate's vigorous research activity and scientific independence.

6. Critical Remarks

The primary critical remarks concern Chapter 2. titled "Motivation and scope of the thesis." In my opinion, it would be advisable for the Doctoral Candidate to consider formulating both a scientific objective and a utilitarian objective, which naturally suggests

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itself after reviewing the content of the dissertation. Defining these scientific and utilitarian aims would enable the formulation of research hypotheses that correspond to them appropriately. I believe that it would also be advisable to clearly specify the novelty of the conducted research in the dissertation, both in the abstract and in the section discussing the rationale for undertaking the topic and the aim of the study, i.e., "Motivation and scope of the thesis."

In the literature review section, it is advisable to conduct a critical review of the literature data related to the discussed subject matter. In this respect, specific subsections require particular refinement: 1.6.1. "Power and biomass to methane"; 1.6.2. "Power and biomass to methanol"; 1.6.3. "Power and biomass to ammonia"; 1.6.4. "Power and biomass to jet fuel." In these subsections, the literature review is not extensive; for example, in some cases, the entire subsection relies on a single literature source.

Moreover, the Doctoral Candidate should consider consolidating the text and merging subsections 1.6.1.–1.6.4., 1.7. "Summary" and 1.8. "State of the Art" into a single section entitled "State of the Art", devoted to hydrogen-based technologies used for the production of biomethanol, ammonia, and jet fuels. After that, the Candidate should proceed to a detailed description of the proposed technological solutions, as presented in the later parts of the dissertation.

The title of subsection 1.7. "Summary" on page 20 is vague and requires clarification and expansion, as it does not specify precisely what is being summarized.

Similarly, as in subsection 1.7. the title of subsection 1.8. "State of the Art" requires clarification as to the scope in which the existing state of knowledge will be reviewed.

Detailed Remarks

- In my opinion, the table of contents should be placed after the Acknowledgements section, while the Appendix should follow the list of references, as is customary.

- It would be advisable to highlight the main chapters and clearly mark the subsections in the table of contents to improve its readability.
- A typographical error appears in the table of contents, namely in item 5.2.: "Improved biogas-to-methanol with power and natural gas production".
- Not all abbreviations have been explained in the Nomenclature section, e.g., CCS.
- In the Introduction on page 10, the same data regarding the reduction of greenhouse gas emissions by at least 55% by 2030 and achieving complete climate neutrality by 2050 is repeated twice.
- In subsection 1.2. "Biomass Conversion", the Doctoral Candidate describes the main products of biomass conversion through anaerobic digestion; however, in my opinion, it would be advisable to provide more detailed information on the production of biogas from various types of biomass, as this directly relates to the topic of the dissertation, i.e., the biogas-methanol configuration.
- Due to thematic overlap, it would be reasonable to merge Chapter 1.3. "Hydrogen production", with subsection 1.4. "Hydrogen production using electrolysis cells", indicating that one of the most promising hydrogen production methods is the technology based on solid oxide electrolysis.
- I suggest replacing citations in the form "[18], [19], [20]" with "[18–20]", and instead of "... ions as charge carriers "[10], [11]" use "[10, 11]". This comment applies to the entire dissertation.
- In Chapter 1.3. Hydrogen production, there are no literature references associated with individual paragraphs.
- On page 16, three-quarters of the text references the same source [8].
- In my opinion, the sentence below is stylistically incorrect and requires clarification – page 19, subsection 1.6.1. "Power and biomass to methane":
  "Biomass-to-methane (BtM), where H_2 contained in syngas limits conversion and unreacted CO_2 is captured downstream. And power-to-methane (PtM), where

surplus renewable electricity produces additional H_2 via electrolysis and the co-produced O_2 is valorized as a steam-oxy gasifying agent, enriching carbon oxides and avoiding N_2 dilution."

- The following statement requires clarification – page 19, subsection 1.6.1. "Power and biomass to methane":
  "Under 2022 market conditions, PtM becomes cost-competitive against natural gas part or most of the year, while all concepts provide grid-injectable biomethane and a pathway for long-duration energy storage using existing gas infrastructure [17]."
- A citation referring to research conducted by specific scientists must include their names – page 24, subsection 1.8.3. "State of the Art in ammonia production":
  "A comprehensive economic study on green ammonia production, based on electrolyzer technology and wind and solar energy for 350 locations in 70 countries, was made by [59]."
- The quality of the figures included in the dissertation is insufficient and requires improvement; the figures should also be standardized (e.g., Figures 3.4, 3.6, 3.7, 3.9, 3.11, 3.12, 3.15).
- The quality and notation of some labels need correction in Figures 3.2, 3.8, and 3.13 (missing subscripts).
- When using the statement "Main input data and assumptions of the proposed subsystems in this chapter are reported in the Appendix," it would be advisable to refer to specific tables or figures – page 30, Chapter 3. "Process modeling of subsystems for hydrogen utilization".
- In the title of Table 3.4 Comparison between the theoretical data for CO conversion and H_2 recovery with those of ref. [106]., a subscript is missing – page 41, subsection 3.7. "Power and Natural Gas Production Subsystem".
- The statement below and its reference to source [92] require clarification – page 54, subsection 4.2.1. "Consequential LCA using Impact 2002+":

"Additional process cycles were simulated using Aspen Plus, and operational data on the mass and energy dynamics of the biogas plant were provided in ref. [92]."

The remaining editorial and stylistic errors I noted do not diminish the value of the dissertation; therefore, I have not included them in the review.

7. Final Conclusions

In summary, I assess the doctoral dissertation submitted for review by Mr. Hamed Ghiasirad, M.Sc. Eng., as highly valuable. The Doctoral Candidate demonstrated excellent command of research tools as well as innovation in addressing the established research objective. The dissertation presents novel elements and constitutes a significant extension of research on polygeneration systems that employ hydrogen as an energy carrier, aligning with the concept of "zero waste." Although the thesis is not free from specific errors and inconsistencies, they fall within the acceptable range for academic work and do not constitute fundamental flaws; therefore, they do not affect the overall, very positive evaluation of the dissertation.

Summarizing the assessment of the doctoral dissertation submitted for review by Mr. Hamed Ghiasirad, M.Sc. In conclusion, it constitutes an original achievement of both cognitive and utilitarian character. The work offers new insights into the potential for optimizing polygeneration systems that utilize hydrogen as an energy carrier. Its applied character, the conducted literature review, the implementation requiring thermodynamic modeling combined with life cycle analysis, as well as the correct interpretation of the obtained research results, all point to the Candidate's extreme scientific competence and independence as a researcher.

Therefore, the doctoral dissertation by Mr. Hamed Ghiasirad, M.Sc. the thesis, entitled "Optimization of polygeneration systems using hydrogen as an energy carrier," fully meets the requirements for doctoral theses specified in Article 187 of the Act of 20

July 2018 on Higher Education and Science (Journal of Laws 2022, item 85). Consequently, I recommend to the Scientific Discipline Council of Environmental Engineering, Mining and Energy at the Silesian University of Technology in Gliwice that the dissertation be admitted to the subsequent steps of the procedure for awarding the doctoral degree in engineering and technical sciences in the discipline of Environmental Engineering, Mining and Energy, and that it be distinguished.

Podpisała Iwona Zawieja

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