Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

Techno-Economics of Interior-Point Optimization for Grid-Integrated Wind-Hydrogen Systems

H. M. Radwan, K. Pope
Department of Mechanical and Mechatronics Engineering, Memorial University of Newfoundland and Labrador, St. John's, NL, Canada

Abstract. Clean hydrogen can be produced by linking wind energy to water electrolyzers. However, the main challenge is the fluctuation in wind power due to varying wind speeds. This can be overcome by connecting the system to the grid. The integration should consider different factors while being implemented. This paper investigates scheduling methods for hydrogen production with alkaline electrolyzers powered by wind energy and grid connectivity. Interior-Point optimization (IP) is used for a scheduling strategy that maximizes revenue and is compared with a rule base scheduling strategy. Operation in several Canadian regions are examined, with a particular focus on Newfoundland and Labrador. The aim is to assess the performance, efficiency, and economic feasibility of diverse energy management strategies. By analyzing the predicted LCOH, hydrogen output, and grid power exchange, the research provides new insights into scheduling approaches for large-scale hydrogen generation from large quantities of intermittent wind resources. Key findings predict Placentia, NL, to have the lowest LCOH of CAD 3.3/kg and Nicolet, QC, to have the highest LCOH (CAD 14.8 to 16.1/kg). Both scheduling strategies produced a similar LCOH for locations with high average wind speeds. However, the IP optimization method resulted in a significantly lower LCOH for locations with low average wind speeds. These insights highlight the importance of tailored scheduling strategies to optimize hydrogen production and promote sustainable energy solutions in various geographic contexts.

Keywords; Alkaline electrolyser, IP optimization, scheduling methods, wind-hydrogen system, clean hydrogen production.

I. INTRODUCTION

Many countries are heavily investing in the development of clean hydrogen production for achieving decarbonization and carbon neutrality goals [1]. Alkaline electrolyzers, known for their cost-effectiveness in large-scale hydrogen production, have obstacles when powered by variable renewable energy sources such as wind and solar. These challenges include shortened electrolyzer lifespan, reduced hydrogen production efficiency, and potential safety hazards [2, 3]. Optimizing control strategies for electrolyzers presents an effective approach to mitigating these challenges and has is a major area of research [4]. Numerous studies have investigated the feasibility of wind hydrogen systems. Messaoudi et al. [5] used a GIS-based approach to evaluate Algeria's wind to hydrogen potential, and demonstrated significant variability in LCOH depending on location and turbine selection. Similarly, research in Argentina examined optimizing wind farm design and infrastructure to reduce LCOH, noting that dispatch constraints impact both LCOH and hydrogen production [6]. A study in Port au Port, Newfoundland and Labrador, optimized the system for cost-effective wind hydrogen production. The study highlighted the significant impact of storage strategies on the LCOH [7]. Karayel and Dincer also assessed Canada's onshore wind hydrogen potential, estimating the capacity with notable contributions from Newfoundland and Labrador [8]. Alkaline, proton exchange membrane, and solid oxide electrolyzers are the primary options, with alkaline electrolyzers currently exhibiting robustness, cost-effectiveness, and suitability for large-scale hydrogen production despite their slower response time compared to PEM electrolyzers [9, 10].

The efficiency of alkaline electrolyzers is critical for their performance and economic viability in hydrogen production. They typically achieve 50-60% voltage efficiency and high Faraday efficiency, which are influenced by parameters such as current density and temperature [3, 11]. By managing these factors, alkaline electrolyzers can maintain high efficiency, enabling feasible hydrogen generation by minimizing energy loss and costs [3]. Several studies have investigated control strategies to optimize the operation of electrolyzers when coupled with renewable energy. Bhandari et al. [12] developed a fuzzy logic control for a grid connected wind hydrogen system, which improved power management and utilization of renewable energy. Liang et al. [13] introduced a Pelican Optimization Algorithm-based scheduling approach for a large-scale, off-grid wind-hydrogen system with multiple storage tanks and alkaline electrolyzers, aiming to maximize hydrogen output, minimize costs, and extend electrolyzer lifespan. Mikovits et al. [14] used a generation scheduling model in Sweden to study the impact of thermal power on electrolyzer under various weather conditions. Hossain et al. [15] employed a delayed switching strategy to reduce the number of start/stop cycles for the electrolyzers, though its reliance on specific wind data may limit broader applicability. Other researchers focused on different control methods, including the integration of supercapacitors [16], segmented startup strategies [16, 17], equal force allocation and rotation strategies [18], and artificial bee colony algorithms [19].

The Interior-Point Algorithm (IP) is a robust and efficient optimization method widely used for solving large-scale nonlinear problems with constraints. Unlike traditional methods that adhere to the boundaries of feasible regions, this approach navigates through the interior of these regions, employing a barrier function to ensure constraint satisfaction and avoid boundary violations [20]. By iteratively updating the solution within these confines, the algorithm converges toward an optimal solution from within the feasible area. In applications involving nonlinear optimization problems, such as engineering design, resource allocation, and control systems, the IP Algorithm showcases its strength in handling complex constraints and high-dimensional data. Its ability to efficiently manage both equality and inequality constraints makes it highly suitable for practical engineering applications where stringent constraints often define feasible solutions [21, 22]. The algorithm's robustness, scalability, and adaptability to various problem contexts underscore its significant role in modern nonlinear optimization [23].

This study compares two scheduling methodologies for an on-grid, onshore alkaline electrolyzer wind-to-hydrogen system in various Canadian regions, with a focus on Newfoundland and Labrador. The goal of this research is to assess various energy management strategies to improve the performance, efficiency, and economic viability of an integrated wind-to-hydrogen production system. By analyzing the LCOH, hydrogen production, and grid power exchange, the study investigates effective scheduling methods for large-scale, continuous hydrogen generation from intermittent wind power, adapted to the specific geographic and environmental conditions of the regions.

II. METHODOLOGY

This paper focuses on four locations in Newfoundland - Stephenville, Placentia, Winterland, and Lewisporte - selected due to their strong wind resources, as they were identified for wind-hydrogen projects by the Government of Newfoundland in 2023 [24]. These locations were compared to two additional sites in Canada: Nicolet, Quebec, and Lethbridge, Alberta. The analysis utilized hourly wind data from 2024, provided by the Candaian Environment and Natural Resources Department [25]. The turbine power ($P_{Turbine}$) is calculated using Equation (1), which considers the air density (ρ), power coefficient (C_p), and wind speed at the turbine height (V_{wind}). Furthermore, the swept area of the wind turbine blades, which involves the blade diameter (Bd). Wind turbine power output (P_g) is calculated based on operational parameters. The turbine operates between the cut-in wind speed (C_{t-in}) and cut-out wind speed (C_{t-out}), reaching rated capacity ($P_{t-rated}$) at wind speeds between the rated speed (v_{rated}) and the cut-out speed (C_{t-out}), as presented in Equation (2).

$$P_{\text{Turbine}} = \frac{1}{2}\left(\rho\, C_p \frac{\pi}{1000}\left(\frac{Bd}{2}\right)^2\ V_{\text{wind}}^3\right) \quad (1)$$

$$P_g = \begin{cases} 0, & \text{if } \mathrm{V_{wind}} < C_{t-in} \text{ or } \mathrm{V_{wind}} > C_{t-out} \\ P_{t-rated}, & \text{if } \mathrm{V_{wind}} > v_{rated} \text{ or } P_{Turbine} > P_{t-rated} \\ P_{Turbine}, & \text{Otherwise} \end{cases} \quad (2)$$

The electrolyzers have specific operational requirements, such as a minimum power threshold, to prevent the formation of explosive gas mixtures. Ensuring proper monitoring and control of operational and safety parameters is important for the long-term reliability and safe operation of alkaline electrolyzers [26]. For this study, a 60 MW wind power project with 10 turbines is selected, with a hydrogen production capacity to wind turbine capacity ratio of 1 : 0.75. This corresponds to 5 alkaline electrolyzers, 4 with a rated power of 10 MW each and one with a rated power of 5 MW, totaling 45 MW of rated power. The electrolyzers are assumed to have a system efficiency of 60% [27].

This study examines two energy management approaches for a wind-to-hydrogen system. Both strategies ensure continuous operation for the electrolyzers within the safety range of P_{min} and P_{rated}. Strategy 1 is rule based, it starts by distributing the turbine power to the first electrolyzer until it reaches P_{rated}, then moves on to the next one until the turbine power is fully utilized. If the power is insufficient to run all electrolyzers, the grid supplies additional power to ensure the remaining electrolyzers operate at P_{min}. Strategy 2 optimizes revenue from hydrogen production using the IP optimization algorithm. This method can distribute power to the electrolyzers either in parallel or in series, ensuring that turbine power is first utilized to run all electrolyzers at P_{min}. Additional power is then drawn from the grid as long as it maximizes revenue.

The objective of the IP optimization is to maximize hourly revenue (C), as defined in Equation (3). This is achieved by calculating the difference between revenue and costs. The revenue is determined by the hydrogen price (C_{H2}= *14.7 CAD/kg*), the inverse of power consumed per unit of hydrogen (q_{H2}= *0.05 MW/kg*), and the sum of power consumed by each electrolyzer (P_i) over a time interval Δt. The costs include a start-up cost (C_{on}) of 100 CAD and an operating cost (C_m) of 3.88 *CAD/MW* [13]. Equation (4) introduces the constraints, ensuring that generated wind power (P_g) equals the sum of power consumed by the electrolyzers and power sold to the grid (P_{Sold}). Furthermore, electrolyzer operation is constrained between a minimum power (P_{min}) and a rated power (P_{rated}), where P_{min} is defined as 10% of P_{rated}.

$$max\ C = \frac{C_{H_2}}{q_{H_2}} \sum \mathrm{P_i}\ \Delta t\ - C_{on}\ \mathrm{N}\,\Delta t - C_m \sum_{i=1}^{n} P_i\ \Delta t \quad (3)$$

$$\begin{cases} P_{min} \le P_i \le P_{i,rated} \\ P_{\mathrm{g}} = \sum_{i=1}^{n} P_i + P_{\text{Sold}} \end{cases} \quad (4)$$

The LCOH, Equation (5), is an important metric for assessing the economic feasibility of a wind hydrogen system. The cost of grid power is assumed to be 90 CAD per megawatt-hour, while the selling price of grid power is set at 50 CAD per megawatt-hour [7, 13]. To compute the LCOH, the annual cost and yearly hydrogen production are considered. The annual cost includes the total annualized capital expenditures and operational and maintenance costs, which are assumed to be 2% of the total capital expenditures [28]. The capital recovery factor (*crf*) is calculated in Equation (6), where the discount rate (r) is 7%, and the technology's lifetime (T_i) is 20 years [7, 13].

$$LCOH = \frac{\text{Annual cost}}{\text{Yearly } H_2 \text{ production}} \quad (5)$$

$$\text{crf} = \frac{r \times (1+r)^{T_i}}{(1+r)^{T_i} - 1} \quad (6)$$

III. Results and Discussion

This section presents an analysis of 2024 wind speed data across six locations and the associated hydrogen production effectiveness with the scheduling methodologies. The LCOH, hydrogen production, and power exchange with the grid are investigated to highlight the effect of different wind resources on the effectiveness of the scheduling methodologies. The analysis of hourly wind speeds for 2024, as illustrated in Figure 1, has significant variability across the six studied locations. In Placentia, NL, wind speeds exceed 7 m/s approximately 63% of the time, which is notably higher than in Nicolet, QC, where this threshold is surpassed only 6% of the time. Winterland, NL, and Stephenville, NL, exhibit similar wind speed distributions, with wind speeds above 7 m/s occurring 35% of the time, while in Lewisporte, NL, this occurs 43% of the time. In Lethbridge, AB, wind speeds surpass 7 m/s 25% of the time, situating it between Newfoundland and Nicolet, QC in terms of wind resource availability.

The wind speed variations directly impact the LCOH. As illustrated in Figure 2, in Newfoundland, the predicted LCOH ranges from CAD 3.3 to 6.1 per kg, with Placentia predicted to be the lowest LCOH. The differences in LCOH between the rule base and the IP methods are minimal for the Newfoundland locations, with the IP method predicted to be only CAD 0.1/kg less expensive. However, for locations outside Newfoundland, the LCOH rises to CAD 7.6/kg in Lethbridge, AB, and CAD 14.8/kg in Nicolet, QC. The efficiency advantage of the IP method is more pronounced in locations with lower wind speeds. In Nicolet, the predicted LCOH increases from CAD 14.8 to 16.1 per kg when switching from the IP method to the rule base method. Similarly, in Lethbridge, AB, the predicted LCOH changes from CAD 7.6 to 8.1 per kg for the rule base method. These values align with a previous study conducted in Stephenville, NL, for a larger project, reporting an LCOH between 4.8 and 6.78 CAD/kg [7]. Similarly, the LCOH for 56 onshore locations globally, with wind speeds ranging from 2-8 m/s, reported an LCOH range of 2.11 to 14 CAD/kg [29].

Figure 3 illustrates the impact of location on hydrogen production. Placentia is predicted to produce approximately 4.7 million kg of hydrogen annually, while Nicolet, QC, can only produce 1.3 million kg for the same project scale. The other locations' predicted production levels vary based on their wind speed potential. The IP method generates more hydrogen in all locations, with an increase of 1% to 4% in Newfoundland and 5% in Lethbridge. In Nicolet, the production increase reaches 10%. The power exchange between the system and the grid, illustrated in Figure 4, shows positive values indicating power supply from wind turbines to the grid and negative values indicating power transfer from the grid to the electrolyzers. Placentia, NL, has the highest predicted, supplying approximately 47 GW annually to the grid while consuming only 13 GW. In contrast, Nicolet, QC, supplies only 1 GW to the grid while consuming 33 GW annually. Lewisporte, NL, supplies around 4.5 GW more to the grid than it consumes annually. Placentia and Winterland, NL, consume 2 - 3 GW more than they supply to the grid. Finally, Lethbridge, AB, consumes around 20 GW while supplying 14 GW. The results will vary significantly if the hydrogen production capacity to wind turbine capacity ratio of 1 : 0.75 is altered. For instance, a ratio of 1 : 1 implies that the hydrogen electrolyzers will have the same rated power as the wind turbines. Consequently, due to the variability in wind power, the system will draw more power from the grid, which may be feasible for locations such as Placentia, NL. However, for locations similar to Nicolet, QC, a ratio of 1 : 0.5 or lower should be considered. This lower ratio would ensure that the electrolyzers have a lower rated power, allowing them to operate sufficiently even when wind power is low. It is recommended that further analysis be conducted to investigate the impact of this ratio more comprehensively.

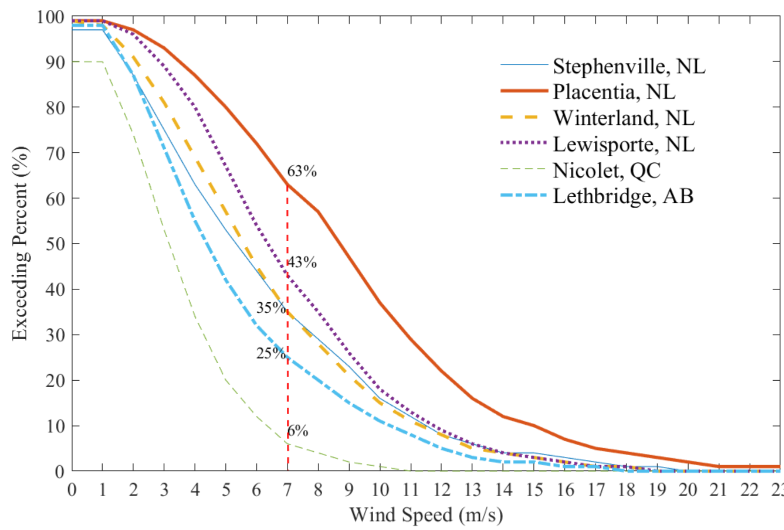

Figure 1: Exceeding percent for wind speed at different locations in Canada at 125 m hub high

Figure 2: LCOH for different locations in Canada, (Pink) IP method, (Orange) rule-base method

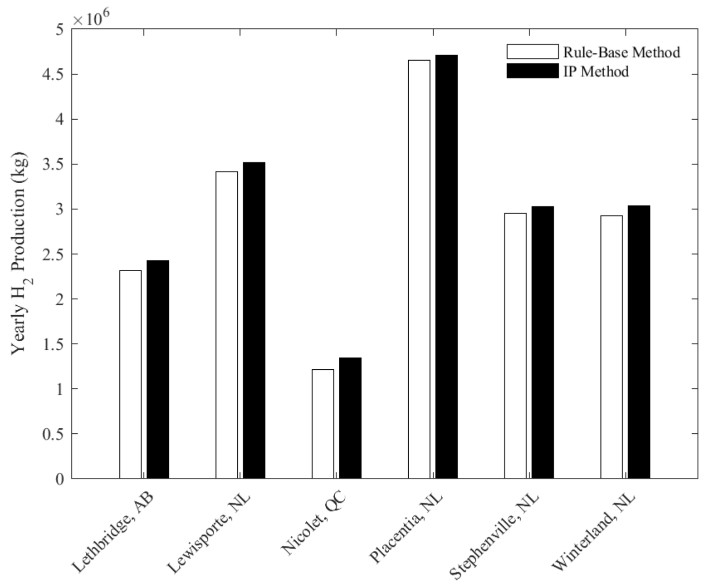

Figure 3: Hydrogen production comparison using rule-base and IP method for different locations in Canada

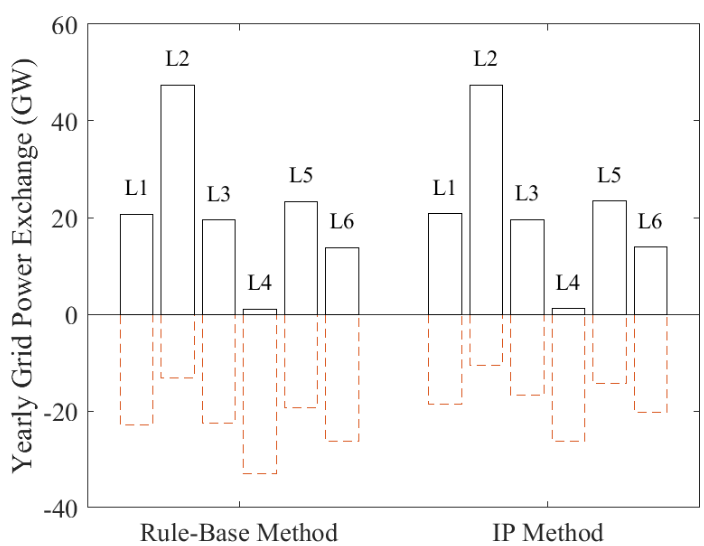

Figure 4: Comparison of grid power exchange for different locations in Canada, (L1) Stephenville, NL, (L2) Placentia, NL, (L3) Winterland, NL, (L4) Nicolet, QC, (L5) Lewisporte, NL, (L6) Lethbridge, AB

IV. Conclusion

Producing green hydrogen by harnessing wind energy through water electrolyzers presents a promising solution. Nonetheless, the variability in wind power caused by changing wind speeds poses a significant challenge. This issue can be mitigated by integrating the system with the grid, which must account for various factors during implementation. This study compared two scheduling methodologies for an on-grid, onshore alkaline electrolyzer wind-hydrogen system in various Canadian regions, focusing on Newfoundland and Labrador. The primary objective was to assess the performance, efficiency, and economic feasibility of energy management strategies.

Key results showed significant variability in wind resources, impacting the predicted LCOH, hydrogen production, and power exchange. In Placentia, NL, wind speeds exceeded 7 m/s 63% of the time, resulting in an LCOH of CAD 3.3/kg. In contrast, Nicolet, QC had wind speeds above 7 m/s only 6% of the time, with an LCOH of CAD 14.8 to 16.1/kg. Hydrogen production in Placentia was approximately 4.7 million kg annually, compared to 1.3 million kg in Nicolet. Placentia also supplied 47 GW to the grid while consuming 13 GW, whereas Nicolet supplied 1 GW and consumed 33 GW. The rest of the locations yielded values in between Placentia and Nicolet, depending on their average wind speed. At locations with high wind speed, both the rule base and IP methods yielded a similar LCOH, while for locations with lower wind speed, there was a significant improvement in reducing the LCOH using the IP method.

This research contributes to better scheduling methodologies for large-scale, continuous hydrogen generation from renewable wind resources. By highlighting the importance of site-specific assessments, this study provides valuable insights for enhancing the efficiency and economic viability of wind-hydrogen systems.

Acknowledgment

The authors of this paper gratefully acknowledge the financial support of the Green Transition Fund from the Government of Newfoundland and Labrador, as well as the Atlantic Canada Opportunities Agency and Natural Sciences and Engineering Research Council of Canada.

References

[1] N. R. Canada, “Hydrogen Strategy for Canada: Progress Report,” Natural Resources Canada, Feb. 2024. Accessed: Jan. 22, 2025. [Online]. Available: https://natural-resources.canada.ca/climate-change/canadas-green-future/the-hydrogen-strategy/hydrogen-strategy-for-canada-progress-report/25678

[2] E. B. Agyekum, C. Nutakor, A. M. Agwa, and S. Kamel, “A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation,” Membranes, vol. 12, no. 2, p. 173, Feb. 2022, doi: 10.3390/membranes12020173.

[3] B. B. Choi, J. H. Jo, T. Lee, S.-Y. Jeon, J. Kim, and Y.-S. Yoo, “Operational Characteristics of High-Performance kW class Alkaline Electrolyzer Stack for Green Hydrogen Production,” J. Electrochem. Sci. Technol, vol. 12, no. 3, pp. 302–307, Aug. 2021, doi: 10.33961/jecst.2021.00031.

[4] B. L. H. Nguyen, M. Panwar, R. Hovsapian, Y. Agalgaonkar, and T. Vu, “Hierarchical Control of Grid-Connected Hydrogen Electrolyzer Providing Grid Services,” in 2022 IEEE 1st Industrial Electronics Society Annual On-Line Conference (ONCON), Dec. 2022, pp. 1–6. doi: 10.1109/ONCON56984.2022.10126806.

[5] D. Messaoudi, N. Settou, and A. Allouhi, “Geographical, technical, economic, and environmental potential for wind to hydrogen production in Algeria: GIS-based approach,” International Journal of Hydrogen Energy, vol. 50, pp. 142–160, Jan. 2024, doi: 10.1016/j.ijhydene.2023.07.263.

[6] I. Schmidhalter, M. C. Mussati, S. F. Mussati, D. G. Oliva, M. Fuentes, and P. A. Aguirre, “Green hydrogen levelized cost assessment from wind energy in Argentina with dispatch constraints,” International Journal of Hydrogen Energy, vol. 53, pp. 1083–1096, Jan. 2024, doi: 10.1016/j.ijhydene.2023.12.052.

[7] D. Timalsina and D. Ghahremanlou, “Optimizing Wind-to-Hydrogen Production in Newfoundland for Export: A Techno-Economic Perspective,” European Journal of Energy Research, vol. 4, no. 2, Art. no. 2, Jun. 2024, doi: 10.24018/ejenergy.2024.4.2.139.

[8] G. K. Karayel and I. Dincer, “A study on green hydrogen production potential of Canada with onshore and offshore wind power,” Journal of Cleaner Production, vol. 437, p. 140660, Jan. 2024, doi: 10.1016/j.jclepro.2024.140660.

[9] S. A. Grigoriev, V. N. Fateev, D. G. Bessarabov, and P. Millet, “Current status, research trends, and challenges in water electrolysis science and technology,” International Journal of Hydrogen Energy, vol. 45, no. 49, pp. 26036–26058, Oct. 2020, doi: 10.1016/j.ijhydene.2020.03.109.

[10] A. Hauch et al., “Recent advances in solid oxide cell technology for electrolysis,” Science, vol. 370, no. 6513, p. eaba6118, Oct. 2020, doi: 10.1126/science.aba6118.

[11] S. Wongsakulphasatch, A. E. Rodrigues, S. Assabumrungrat, and P. Kim-Lohsoontorn, Hydrogen Production Technologies. Basel, Switzerland: MDPI - Multidisciplinary Digital Publishing Institute, 2021. doi: 10.3390/books978-3-03943-668-2.

[12] B. Venkateswara Rao, R. Devarapalli, H. Malik, S. K. Bali, F. P. García Márquez, and T. Chiranjeevi, “Wind integrated power system to reduce emission: An application of Bat algorithm,” IFS, vol. 42, no. 2, pp. 1041–1049, Jan. 2022, doi: 10.3233/JIFS-189770.

[13] T. Liang, M. Chen, J. Tan, Y. Jing, L. Lv, and W. Yang, “Large-scale off-grid wind power hydrogen production multi-tank combination operation law and scheduling strategy taking into account alkaline electrolyzer characteristics,” Renewable Energy, vol. 232, p. 121122, Oct. 2024, doi: 10.1016/j.renene.2024.121122.

[14] C. Mikovits, E. Wetterlund, S. Wehrle, J. Baumgartner, and J. Schmidt, “Stronger together: Multi-annual variability of hydrogen production supported by wind power in Sweden,” Applied Energy, vol. 282, p. 116082, Jan. 2021, doi: 10.1016/j.apenergy.2020.116082.

[15] M. M. Hossain, M. R. I. Sheikh, and P. S. Rahman, “Cooperatively controlling of grid connected DFIG based wind turbine with hydrogen generation system,” in 2015 International Conference on Electrical & Electronic Engineering (ICEEE), Nov. 2015, pp. 233–236. doi: 10.1109/CEEE.2015.7428265.

[16] R. Fang and Y. Liang, “Control strategy of electrolyzer in a wind-hydrogen system considering the constraints of switching times,” International Journal of Hydrogen Energy, vol. 44, no. 46, pp. 25104–25111, Sep. 2019, doi: 10.1016/j.ijhydene.2019.03.033.

[17] G. Zhang and X. Wan, “A wind-hydrogen energy storage system model for massive wind energy curtailment,” International Journal of Hydrogen Energy, vol. 39, no. 3, pp. 1243–1252, Jan. 2014, doi: 10.1016/j.ijhydene.2013.11.003.

[18] Y. Li et al., “Exploration of the configuration and operation rule of the multi-electrolyzers hybrid system of large-scale alkaline water hydrogen production system,” Applied Energy, vol. 331, p. 120413, Feb. 2023, doi: 10.1016/j.apenergy.2022.120413.

[19] Z. Hong, Z. Wei, and X. Han, “Optimization scheduling control strategy of wind-hydrogen system considering hydrogen production efficiency,” Journal of Energy Storage, vol. 47, p. 103609, Mar. 2022, doi: 10.1016/j.est.2021.103609.

[20] A. S. Nemirovski and M. J. Todd, “Interior-point methods for optimization,” Acta Numerica, vol. 17, pp. 191–234, May 2008, doi: 10.1017/S0962492906370018.

[21] J. Kardoš, D. Kourounis, and O. Schenk, “Structure Exploiting Interior Point Methods,” Jul. 11, 2019, arXiv: arXiv:1907.05420. doi: 10.48550/arXiv.1907.05420.

[22] T. F. Coleman and J. Liu, “An Interior Point Method for Large Scale Linear Feasibility Problems,” in 2015 International Conference on Computational Intelligence and Communication Networks (CICN), Jabalpur, India: IEEE, Dec. 2015, pp. 1235–1237. doi: 10.1109/CICN.2015.237.

[23] J. T. Betts, Practical Methods for Optimal Control Using Nonlinear Programming, Third Edition. Philadelphia, PA: Society for Industrial and Applied Mathematics, 2020. doi: 10.1137/1.9781611976199.

[24] Government of Newfoundland and Labrador, Department of Industry, Energy and Technology, Office of the Deputy Minister, “Wind Application Recommendation Letter,” Aug. 30, 2023. [Online]. Available: https://www.gov.nl.ca/iet/files/Wind-Application-Recommendation-Letters.pdf

[25] S. Canada, “Environment and natural resources.” Accessed: Jan. 26, 2025. [Online]. Available: https://www.canada.ca/en/services/environment.html

[26] F. Dawood, M. Anda, and G. M. Shafiullah, “Hydrogen production for energy: An overview,” International Journal of Hydrogen Energy, vol. 45, no. 7, pp. 3847–3869, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.059.

[27] “Hydrogen Insights 2024,” The Hydrogen Council, Sep. 2024. [Online]. Available: https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf

[28] E. Way, “Project Nujio’qonik GH2,” W. E. GH2 Inc, Jun. 2022. [Online]. Available: https://www.gov.nl.ca/ecc/file/2202-Registration-Document.pdf

[29] Y. Zheng, S. You, C. Huang, and X. Jin, “Model-based economic analysis of off-grid wind/hydrogen systems,” Renewable and Sustainable Energy Reviews, vol. 187, p. 113763, Nov. 2023, doi: 10.1016/j.rser.2023.113763.