Operational Strategies and Integrated Design for Producing Green Hydrogen from Wind Electricity

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Abstract

Realizing the potential of renewable hydrogen production requires flexible operation of electrolysis systems to integrate with intermittent power sources. This work develops an optimization model to assess flexible operational strategies for alkaline and proton exchange membrane (PEM) electrolysers powered by wind energy. The model quantitatively analyses trade-offs between electrolyser shutdown strategies, overloading capacities, and battery integration to identify optimal regimes balancing efficiency, flexibility, and economics. The results reveal a mixed-integer linear programming approach can optimize system configurations and control strategies to minimize the levelized cost of hydrogen production. Optimal near-minimum load operation is achieved by independently optimizing the load of each electrolyser block, while avoiding shutdowns above a critical load level. Strategic electrolyser overloading can provide economic benefits by reducing installed capital costs, if technical feasibility and accelerated degradation are addressed. Battery energy storage integration significantly improves economics by enhancing asset utilization, provided excess renewable energy is available. The model provides novel insights on integrating alkaline and PEM electrolysis with intermittent wind power to advance renewable hydrogen production. Quantifying trade-offs between operational flexibility and economics will help guide flexible design and control strategies for cost-optimal renewable electrolysis systems.

Keywords: Alkaline Electrolyser Cell (AEC), Polymer Electrolyte Membrane electrolyser Cell (PEMEC), Battery Energy Storage System, Overload Operation, Mixed-integer Linear Programming (MILP), Optimization, Techno-economic Analysis

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1. Introduction

Hydrogen is poised to play a pivotal role in transitioning to a climate-neutral economy by enabling emission-free operations across industrial, transportation, and residential sectors [1]. The "power-to-hydrogen" pathway, which involves the electrochemical conversion of electricity into hydrogen and oxygen, is particularly promising for achieving a net-zero emission energy sector [2], [3]. This process is advantageous as it leverages excess and environmentally friendly electricity, notably from renewable sources like wind and solar, which, despite their potential, are plagued by unpredictability and intermittency [4]. The transformation of "green electricity" into "green hydrogen" presents novel solutions for managing the variability of renewable energy production. Specifically, using wind power for hydrogen generation heralds a new era of sustainable energy supply, including the provision of fuel and chemicals, with the added benefit of combustion that leaves no carbon footprint. Life cycle assessments have shown that emissions are confined to the manufacturing phase of the equipment used, which are significantly lower than those associated with fossil fuel-based systems [5]. Furthermore, hydrogen's high energy density makes it an excellent option for mitigating the challenges posed by wind intermittency, expanding its application range significantly [6]. This approach also facilitates the integration of offshore wind energy into the gas grid and supports on-demand power generation through green gas storage, thereby reducing carbon intensity [7].

Forecasts suggest that focusing on hydrogen and renewable gas for the development of the EU's energy infrastructure could be more economical than pursuing widespread electrification [1]. The European Green Deal has established rigorous goals to achieve net-zero greenhouse gas (GHG) emissions by 2050 [8]. The "FIT FOR 55" initiative is designed to cut GHG emissions by 55% by 2030 relative to the levels of 1990 [9]. The more recent REPowerEU Plan [10] envisions a reduced role for natural gas as a bridge fuel and advocates for an accelerated expansion of the EU's electricity grid and hydrogen infrastructure through substantial investments. This plan includes an ambitious objective of producing and importing 20 million tonnes of renewable hydrogen by 2030. Although China stands as the leading producer and consumer of hydrogen, a mere fraction (about 1.5%) is currently produced via electrolysis. Nevertheless, China's new hydrogen strategy indicates a significant move towards renewable hydrogen [11]. The International Energy Agency (IEA) has highlighted the need for a dramatic increase in hydrogen usage - up to sixfold - to meet the objectives of a net-zero global energy sector by 2050 [3].

In the United Kingdom, wind power achieved a record production level of 17.2 GW on December 18, 2021, surpassing previous milestones. Earlier, in August 2021, wind power constituted the largest portion of the UK's power generation, accounting for 60% of the total. This trend suggests the potential for offshore wind power generation to significantly outstrip onshore demand in the future [12].

Water electrolyzer systems are highly adaptable and flexible, making them ideal for integration with various processes through mass and thermal energy integration. This adaptability is crucial given the intermittent and unpredictable nature of renewable energy sources. Notable examples of such integrations include: combining in-situ hydrogen storage solutions [13], integrating Organic Rankine Cycles (ORC) powered by geothermal systems with PEM electrolyzers [14], leveraging concentrated solar systems to assist solid oxide electrolyzers [15], coupling photovoltaic panels with PEM electrolyzers [16], utilizing wind energy to power alkaline water electrolyzers [17], generating micropower through the tandem operation of microfluidic electrolyzers with microfluidic fuel cells [18], integrating building-integrated photovoltaics (BIPV) with electrolyzer/fuel cell systems [19], connecting pressurized high-temperature electrolyzers with solar towers [20], and creating grid-independent microgrids that include photovoltaic panels, heat pumps, fuel cells, and electrolyzers [21,22], among other innovative approaches.

The field of hydrogen production through water electrolysis encompasses a vast, multidisciplinary research landscape, where innovations in material engineering, system modeling, technology selection, and operational strategies coalesce. This realm of study is characterized by a quest for enhanced efficiency, durability, and economic viability, addressing the intrinsic challenges of integrating electrolysis with renewable energy sources for a sustainable energy future. The pursuit involves a nuanced exploration of advanced materials, such as hybrid nanocomposite membranes and stainless-steel components, alongside the development of comprehensive models to optimize system performance and energy integration. Furthermore, the comparative analysis of electrolysis technologies and the operational flexibility of these systems highlight the complex trade-offs between cost, efficiency, and scalability. This introductory survey sets the stage for a deeper dive into the multifaceted efforts driving forward the goal of efficient, sustainable, and economically feasible green hydrogen production, marking a pivotal chapter in the transition to renewable energy systems.

In the quest for sustainable and efficient hydrogen production, the engineering of materials used in water electrolysers emerges as a critical frontier. Innovations in material science not only promise to enhance the performance and durability of electrolysis systems but also to challenge conventional paradigms with novel solutions. From the development of hybrid nanocomposite membranes as alternatives to traditional polymers to the utilization of stainless-steel components for increased durability and performance, researchers are actively exploring pathways to optimize electrolyser technology. Abdel-Motagali et al. [23] evaluated the performance and durability of a hybrid nanocomposite (HNC) membrane as an alternative to perfluorosulfonic acid polymers for proton exchange membrane (PEM) water electrolysis. They prepared catalyst-coated membranes (CCMs) using the HNC membrane and tested them in a compact PEM water electrolysis cell, comparing to a reference CCM with Nafion membrane. Initial testing showed the single HNC CCM had a short lifetime of 9.5 hours due to water absorption softening. Sandwiching the HNC between two membranes increased the lifetime to 25.5-150 hours but performance still degraded over time. Upscaling to 250 cm^2 CCMs resulted in inferior performance and lifetime under 11 hours compared to the Nafion reference. Analysis showed the HNC membrane lost 45-95% of ion exchange capacity during testing due to chemical instability in the PEM conditions. The authors identified degradation mechanisms of imine hydrolysis and oxidative damage to the sulfonic acid groups. Although the multilayer CCM approach prolonged lifetime, the results demonstrated core chemical instability issues of the HNC membrane for water electrolysis applications. Stiber et al. [24] developed a high-performance and durable proton exchange membrane (PEM) water electrolyser using stainless steel components, including bipolar plates and porous transport layers. Unlike most PEM electrolysers that use expensive titanium parts, this study demonstrated that stainless steel, when coated with Ti and Nb/Ti, can perform effectively. The electrolyser exhibited impressive overload capability, achieving a current density of 6 A/cm^2 at 80°C with an unprecedented efficiency of 77% at 4 A/cm^2. This performance is comparable to the highest reported for PEM electrolysers. The polarization curve remained steady up to 6 A/cm^2 without any hysteresis, indicating no mass transport losses or degradation at this high current density. The Nb/Ti coated stainless steel porous transport layer allowed for excellent performance at high current densities, eliminating typical mass transport losses. The results suggest a potential for overloading this electrolyser design, with an indication that overloading up to 6 A/cm^2 (50% above the suggested nominal condition) should be feasible for short durations. The coatings provided corrosion protection for over 1000 hours of operation, but further testing is needed to confirm long-term overload capability, indicating a high overload potential of up to at least 150% nominal current density for this stainless-steel PEM electrolyser.

The advancement of hydrogen production technologies through water electrolysis is significantly propelled by sophisticated modeling research. By leveraging computational models alongside experimental validation, researchers are able to navigate the complexities of electrolysis operations, from thermal management to mass transfer dynamics. Such an integrated approach not only predicts system behaviors under varied conditions but also informs the development of more effective and durable electrolysis solutions. Arthur et al. [25] developed and validated computational models to analyse the potential benefits of thermally integrating a membrane distillation heat exchanger (MDHX) with a water electrolysis stack. They modelled an anion exchange membrane (AEM) electrolyser and validated it against published data. They also modelled an MDHX unit using a finite element approach and validated it against experimental flux data. With the validated models, they simulated an integrated MDHX-EC system. Key findings were that the MDHX could utilize waste heat from the electrolyser to regulate its temperature, avoiding external cooling. Additionally, the MDHX could supply sufficient water to meet the electrolyser's needs, with excess produced at higher current densities. Dang et al. [26] developed zero-dimensional mass transfer models in Simulink to analyse the trade-offs between membrane thickness, cathode pressure, and hydrogen crossover in high-pressure PEM electrolysers. They performed simulations from 1-200 bar to quantify the impact of pressure on voltage efficiency and hydrogen permeability. The results showed that a 183 μm Nafion 117 membrane could withstand pressures up to 200 bar with only a 2% voltage penalty compared to atmospheric operation. The authors then, conducted an economic analysis to compare the costs of high-pressure versus atmospheric PEM electrolysis with separate mechanical compression. They developed models considering the capital and operating expenses of each approach. The high-pressure system had slightly higher electrolyser stack costs but avoided the expense of a separate compressor system. The analysis demonstrated that for cathode pressures below 398 bar, direct high-pressure electrolysis was more economical overall than atmospheric operation with compression. Qi et al. [27] developed a frequency-domain thermal model of an alkaline electrolysis system that considers multiple heat capacities and time delays. They used this model to design optimized PID controllers for temperature regulation. The PID parameters were tuned by minimizing overshoot and settling time while ensuring stability. Experiments on a 5 Nm^3/hr electrolyser verified stable control using the designed PID controllers with both stack inlet and outlet temperatures as feedback. The inlet temperature PID showed faster response to load changes while the outlet temperature PID allowed higher efficiency at steady state. Reducing heat transfer delays, such as by optimizing the stack and cooling designs, was found to significantly improve the PID control performance. With 12 minutes of delay, the settling time increased from 0.17 hours to 3.69 hours compared to no delay. Torbjørn Egeland-Eriksen et al. [28] applied simulations to evaluate the feasibility of offshore hydrogen production by integrating a proton exchange membrane (PEM) water electrolyser model with operational data from a 2.3 MW floating offshore wind turbine near Norway. This research addresses the potential for decarbonizing challenging sectors such as shipping and industry through offshore renewable hydrogen production. They developed a detailed PEM electrolyser model in MATLAB/Simulink, utilizing wind power data to compute hydrogen production rates, efficiency, and costs. The model accounted for key voltage losses and pressure effects within a PEM electrolyser cell and demonstrated good alignment with literature-based polarization curves. Five different 31-day periods were analysed, assessing six system configurations with various electrolyser power ratings (1852 kW, 926 kW, 463 kW) and the presence of a Li-ion battery. Production costs ranged from \$4.53 to \$14.49 per kg of H_2, with the lowest cost achieved during high wind (64% capacity factor) and very low electricity prices (0.9 ¢/kWh). The system displayed an overall energy efficiency of 56-57% across all cases. Daoudi and Bounahmidi [29] provided a comprehensive review of alkaline water electrolysis (AWE) modelling approaches, focusing on key physicochemical phenomena governing system performance. They summarized models characterizing electrochemical kinetics, ion/gas transport, thermal effects and multiphase flows within AWE components. The authors highlighted electrochemical models utilizing meaningful parameters like electrode morphology and charge transfer coefficients, gas crossover models incorporating material balances, thermal models representing heat generation/loss, and Eulerian/Lagrangian models examining compartment multiphase flows. They emphasized gaps in integrated modelling of mechanisms influencing electrochemistry, transport processes, and hydrodynamics. Abdin, Webb and Gray [30] developed and tested a detailed model for a proton exchange membrane (PEM) electrolyser cell, emphasizing a physical basis for model parameters. This model includes material and mole balances across the anode and cathode subsystems, models effective binary diffusion through porous electrodes, and accounts for water transport through the PEM and resistances across electrodes, flow field plates, and the PEM itself. By integrating modular mathematical models of the anode, cathode, membrane, and cell voltage, this work offers insights into the electrolyser cell's overall equilibrium performance, influenced by materials and component configuration. The focus on dissecting the contributions of various overpotentials to the cell's polarisation curve is significant because it underlines the model's utility in identifying performance improvement areas. Persson, Mignard and Hogg [31] developed a new model for a 250 kW electrolyser based on plant data from the Levenmouth Community Energy Project in Methil, Scotland. Their focus was on improving the accuracy of electrolyser performance predictions, especially at times of low power input from renewable energy sources. This is important because developers and operators of energy systems that incorporate hydrogen storage need effective models to design and operate these systems efficiently. The novel model combines the Tafel equation with an original model for Faradaic efficiency and was validated against actual plant data. It proved to be more accurate than the 'Linear Model' commonly used in the industry, especially in predicting hydrogen production and managing hot standby losses. The authors observed that initial pressurization, hot standby, and the control scheme significantly affect electrolyser performance. Additionally, their data highlighted the need for an optimized control scheme to minimize losses during low operational periods, suggesting that effective modeling should consider the whole system, including dynamic operation and energy systems integration. Wilberforce et al. [32] developed a mathematical model using MATLAB/Simulink to simulate the integration of various components including a vertical axis wind turbine, a permanent magnet synchronous generator, a rectifier, a DC-DC converter, and a proton exchange membrane (PEM) electrolyzer for the production of green hydrogen. This study aimed to evaluate the system's performance under real-world conditions by using wind speed data from Warwickshire, UK, highlighting the potential for sustainable hydrogen production through the combination of wind energy and electrolyzers. The authors created detailed models for each component based on thermodynamic and electrochemical principles, integrating them into a cohesive system. The simulation covered wind turbine power output and rotor RPM as functions of wind speed, while considering the efficiency and loss mechanisms in the generator, rectifier, and converter, as well as the impact of temperature and pressure on the PEM electrolyzer's performance. The findings indicated that the PEM electrolyzer operates more effectively at higher temperatures and lower pressures, with hydrogen production directly related to wind speed. This integrated modeling approach allows for system optimization and shows the potential for renewable hydrogen production. Berasategi et al. [33] developed a new tool that combines a one-dimensional (1D) analytical model with a three-dimensional (3D) Computational Fluid Dynamics (CFD) model to evaluate proton exchange membrane (PEM) fuel cells' performance. The paper's aim was to create a precise and computationally efficient model for PEM fuel cells and electrolyzers, enhancing their development and understanding. The authors introduced a method that merges the models without altering them individually, using nonlinear regression to integrate the 1D model. Ríos et al. [34] developed a model focused on techno-economic analysis to ascertain the ideal size of electrolyzers for enhancing the economic returns from producing hydrogen using renewable sources. This model utilizes data on renewable energy generation to compute hydrogen production levels and to fine-tune the size of electrolyzers within a range of 1MW to 300MW. They conducted analyses on two scenarios: utilizing offshore wind in Spain and employing solar PV also in Spain. The findings indicated that for offshore wind, the operation reaches economic viability when hydrogen is priced at $5.5/kg, requiring electrolyzers of at least 55MW in capacity. In the case of solar PV, profitability is achievable with hydrogen prices ranging from $3.5 to $7/kg, and the ideal electrolyzer capacity varies from 58MW to 300MW, depending on the hydrogen price. An important contribution of this model is its capability to tailor electrolyzer sizing to the specifics of the renewable resources available, thereby optimizing the financial outcome of the project. The model calculates production volumes, costs, and revenues to pinpoint the scenario that yields the highest profitability. However, the study acknowledges a limitation in its economic evaluation, omitting the potential financial benefits from reduced emissions or contributions to the power grid. Aouali et al. [35] developed a model of a proton exchange membrane (PEM) electrolyser for hydrogen production through water electrolysis. They modeled the PEM electrolyser by considering four physical models - electrical, electrochemical, thermodynamic, and thermal. Equations were formulated based on principles like Faraday's law, Butler-Volmer equation, and Fick's law of diffusion. The model was validated experimentally using a 7-cell PEM electrolyser system. The current-voltage characteristics and temperature profiles from the model showed good agreement with experimental data. This demonstrates the model's capability to describe the dynamic behavior of the PEM electrolyser. One key contribution is using an identification approach to estimate the temperature-dependent electrochemical parameters. The model provides a useful analytical tool to study the impact of operating conditions on PEM electrolyser performance. One limitation is that only low pressure operation below 7 bar was considered. At higher pressures, the polarization curve shape changes significantly. Overall, the modeling and experimental validation enables better understanding of the interacting effects in PEM electrolysers. This supports design and control for efficient renewable hydrogen production. Eichman et al. [36] experimentally tested a proton exchange membrane (PEM) and an alkaline electrolyser to quantify their operational flexibility for potential grid services applications. They performed ramp rate tests, variable operation tests, frequency disturbance correction tests, and startup/shutdown tests on 40 kW PEM and alkaline electrolysers. The testing revealed the electrolysers started modulating their electricity demand within 13-20 milliseconds following a setpoint adjustment, reached new steady-state operation at the setpoint in approximately 1 second, operated at 10% of rated load during turndown tests, helped restore grid frequency faster when providing frequency regulation compared to grid response without electrolyser support, and were able to cold start up in 6 minutes 27 seconds from being completely off. The rapid response time, high ramp rates, wide operating range, and fast startup/shutdown capabilities indicate both PEM and alkaline electrolysers could technically participate in end-user energy management, electricity markets, and support increased renewables integration if properly designed and controlled. Overall, the electrolysers exhibited favourable operating flexibility that could enable multiple applications while also producing hydrogen.

The operational dynamics of electrolyser systems, particularly under transient and part-load conditions, have garnered considerable attention in recent research. This focus is driven by the need to enhance system flexibility and enable seamless integration with fluctuating renewable energy sources. Studies span across various electrolyser technologies and operational scenarios, including the thermal integration of solid oxide electrolysers with concentrated solar systems, the exploration of part-load operations in alkaline electrolysers, and the investigation of transient responses in both renewable and regenerative electrolyser systems. De Lorenzo *et al.*, [15] studied the potential of thermal integration of a concentrated solar system with a solid oxide electrolyser. This will require considering the thermal needs at a steady state, as well as constraints on the temperature variations over transitional operating scenarios such as start-up and shut-down. The authors reported that the need for thermal management due to seasonal variations, where during the summer operations excess heat should be extracted, and conversely an auxiliary thermal source is needed in the winter, for start-up operations. Concerning shut-down operations, natural cooling was found to be too fast, violating the constraints on the temperature gradient. Therefore, thermal storage or a reliable thermal source (e.g., electric) was recommended. Zhang *et al.*, [17] studied the part-load operation of a 50 m^3h^{-1} Alkaline electrolyser pilot plant. They quantified the DC energy efficiency of 4.01 to 4.51 kWh/Nm^3 H_2, for high purity hydrogen production in the range of 30-100% loads. The researcher also reported that safe control of hydrogen content in the oxygen product (50% of lower flammability limit - LFL) can be achieved by controlling the system pressure. The authors indicated that if the safety limit is relaxed to 70% of LFL, the operational range can be further extended to 20-100% loads. Zhang *et al.*, [17] also investigated the transient start-up and shutdown operations, with fast load ramps. They recommended that pressure control has an important role in stabilizing the electrolyser system. Bergen *et al*., [37,38], investigated the transient response of a renewable/regenerative electrolyser/fuel cell system, at a residential scale. They observed that the energy conversion efficiency is a strong function of the transient characteristics of the electrolyser. The authors recommended that performance decline is minimal if the electrolyser current (as well as power input) is kept at a minimum. It has been noted that transitional operations on short time scales, spanning just a few minutes, can markedly accelerate the degradation process of electrolyzer systems. However, allowing for "rest periods" between successive operational cycles can lead to partial recovery, mitigating some of the effects of this accelerated degradation. Petipas, *et al.*, [39] investigate the performance of a Solid Oxide Electrolysis Cell (SOEC) under various part-load operational scenarios. The authors reported that without an external source of thermal energy, the power load is restricted to the range of 60-100%, and beyond such range, an additional heating system is required. Cooper, *et al.* previously developed a framework for the optimal design and operation of a large-scale electrolyser plant powered to minimize the levelized cost of hydrogen [40]. This work found that different power profiles can have a significant impact on the design of the plant, where increased volatility in the power profile causes optimal designs to shift from AWE to PEM. It noted, however, that optimal designs for large plants did often use a mix of technologies in the design to provide different effects. Aboukalam da Cruz et al. [41] developed a dynamic model of an alkaline water electrolysis system to optimize its operating parameters and minimize electricity costs for a given hydrogen yield. They modelled the electrolyser's cell stack, accounting for energy accumulation, and two gas-liquid separators, accounting for mass and energy accumulation. The differential-algebraic equation model captured component mass and energy balances, phase equilibria, and semi-empirical correlations for cell voltage. Orthogonal collocation on finite elements numerically converted the model into an algebraic system suitable for dynamic optimization. Model validation through comparison with experiments showed reasonable agreement. Through optimization, a 17% reduction in annual electricity costs was achieved compared to constant operation, by increasing load during low-cost periods. The modelling methodology demonstrated value for characterizing transients and optimizing system economics. The contributions of this modelling approach were the linking of thermal inertia and electrochemical kinetics along with dynamic optimization. Lebbal and Lecœuche [42] developed a comprehensive model, identification approach, and diagnostic algorithm for proton exchange membrane (PEM) electrolysers, aimed at enhancing the efficiency and safety of hydrogen production through water electrolysis. Their work introduces an analytical model that integrates a steady-state electric model with a dynamic thermal model, formulated on the basis of physical and electrochemical principles. The authors applied experimental data and identification techniques, specifically a nonlinear least squares method for the electric model and a first-order system approach for the thermal model, to estimate model parameters. Utilizing the refined model, they devised a model-based fault diagnosis strategy for the timely detection and isolation of faults in sensors, actuators, or the electrolyser system itself, employing residuals to monitor for discrepancies. Simulation results underscore the model's capacity to identify and segregate various fault types, thereby enhancing the safety and operational reliability of the electrolyser. The paper's core contribution lies in its holistic approach combining modeling, system identification, and model-based monitoring to ensure the health and safety of electrolysers, despite noting a limitation in the lack of real-world application validation. Yin et al. [43] developed a dynamic model for a solid oxide electrolysis system, focusing on its control-oriented dynamic modeling and thermodynamic analysis, important for optimizing control design and operational efficiency amidst renewable energy's intermittency. They addressed voltage losses through an electrochemical mechanism-based model, incorporating stack temperature dynamics and balance of plant components. The model's accuracy was verified against polarization curves under various temperatures, discussing electrolytic voltage effects from temperature and current density. They explored three operational modes (endothermic, thermoneutral, exothermic) based on current density regions, comparing energy consumption across components to identify optimal conditions for maximum efficiency. The electrolyzer was identified as the primary energy and exergy consumption source. Dynamic simulations responded to control inputs and current density disturbances, highlighting the system's response rapidity, variable couplings, and trend variations due to electrochemical reactions, gas flow, and heat transfer. This foundational study supports system optimization and dynamic control strategy design for solid oxide electrolysis systems, crucial for enhancing renewable energy integration through efficient hydrogen production. Lange et al. [44] conducted a technical evaluation of water electrolysis systems to assess their flexibility in integrating renewable energy. They defined flexibility based on parameters like load range, startup time, ramp rate, and load gradient. Four electrolysis technologies were scrutinized: Alkaline Electrolysis (AEL) with a cell voltage range of 1.23-2.25V and efficiency of 63-71%; Proton Exchange Membrane (PEM) with a cell voltage range of 1.23-3V and efficiency of 60-68%; High Temperature (SOEC) with a cell voltage range of 0.72-1.8V and efficiency around 96%; and Anion Exchange Membrane (AEM), still under development. High Temperature SOEC exhibited the highest efficiency but had extended startup times, while PEM demonstrated rapid startup and load gradient. AEL, though a mature technology, had lower current density. Three primary control strategies were elucidated: the "Segment Principle," wherein stacks are activated sequentially until they reach 80% of nominal power; the "Start-stop Principle," which operates stacks exclusively at full nominal power and adds another stack if surplus energy is available; and the "Slow-start Principle," which sets a minimum starting power for each stack. The “segment” approach were recommended. The study emphasized the need for future research to reduce electricity consumption to <45 kWh/kg H_2 by 2050 and enhance current density to >2 A/cm^2. The authors concluded that while electrolysers demonstrated good flexibility, further enhancements in startup time, turndown ratio, and load gradient are vital for accommodating higher renewable energy integration. Varela et al. [45] developed a novel scheduling model for alkaline water electrolysis (AEL) with the aim of determining the optimal design and operation of power-to-x systems that convert intermittent renewable electricity into hydrogen, a significant field of research with implications for grid balancing and decarbonization. The model was constructed as a mixed-integer linear program (MILP) with binary variables representing various AEL operational states and transitions, while continuous variables account for power load and hydrogen flowrate. Various constraints were used to capture AEL operational characteristics. The objective of the model is to maximize hydrogen production while minimizing electricity and investment costs, considering fluctuating renewable supply and electricity prices. The study demonstrates the model's effectiveness by applying it to a 50 MW wind-hydrogen plant case study, yielding valuable insights into energy absorption, production, and cost optimization. Haleem et al. [46] investigated experimentally and theoretically the effects of operation and shutdown parameters and electrode materials on the reverse current phenomenon in alkaline water electrolysers. The authors operated a 4-cell stack alkaline water electrolyser under different electrolysis currents (0.4-1 A/cm^2) and temperatures (30-80°C). After shutting down the electrolyser, they measured the reverse currents, electrode potentials, and electromotive forces over time. Results showed that high temperature and electrolyte circulation during shutdown increased the reverse current and accelerated changes in electrode potentials due to enhanced ionic conductivity. However, the electrolysis current did not significantly influence the reverse current. In addition, bubbling nitrogen to remove dissolved gases did not affect the reverse phenomenon, suggesting it originates from redox reactions of the electrode materials. Furthermore, the cathode attached to a robust anode on the same bipolar plate underwent more oxidation. The introduced model agreed well with experiments and helped explain the behaviour of different bipolar plates. The study provides insights into adapting alkaline water electrolysers to intermittent renewable energy sources. Lee et al. [47] conducted a comprehensive study on hydrogen production via polymer electrolyte membrane (PEM) water electrolysis, aiming to address the challenge of surplus renewable electricity utilization. Their analysis focused on optimizing operating voltages and replacement strategies for PEM electrolysers, considering various parameters, including initial voltages (1.8V and 1.65V), maximum cell voltages (2.0-2.2V), degradation rates (5-20 μV/h), and renewable electricity prices ($0.03-0.5/kWh). Key findings highlighted that the H_2 selling price, maximum cell voltage for replacement, and initial voltage significantly impact economic viability. Lower initial voltages improved financial returns, while more frequent replacements reduced CO_2 emissions. The study also called for future research in areas such as nonlinear degradation rates and dynamic electricity prices. Lebbal and Lecœuche [42] undertook the development of a dynamic model for a Proton Exchange Membrane (PEM) electrolyser, with the objective of optimizing efficiency and ensuring safety in hydrogen production facilities. They concentrated on constructing an analytical-dynamic model to facilitate the control and monitoring of the electrolysis process, emphasizing the importance of precise model parameter identification and the creation of efficient monitoring systems. These efforts were crucial for enhancing the operational safety and efficiency of hydrogen electrolysis stations by enabling the early detection, isolation, and remediation of potential operational faults. Allidieres *et al.*, [48] investigated the capabilities of PEM electrolyser systems considering the grid operational constraints. The authors reported that PEM electrolyser systems are flexible and reactive enough to address the requirements of primary and secondary markets. They also identified two critical aspects to be addressed being (1) reducing efficiency losses through isothermal operation, and (2) managing power fluctuations. Huang *et al*., [49] developed a framework for economic model predictive control (EMPC) of an alkaline electrolyser system for operational scheduling of power, hydrogen, and heat. The authors reported a significant saving over a rule-based operational strategy. Flamm *et al.*, [50] developed a control algorithm based on a receding horizon optimization program. They applied a “gray-box” model using experimental data to incorporate nonlinear aspects such as thermal dynamics, efficiency, and overloading features of the actual system. The controllers successfully satisfied the hydrogen demand using electricity generated from a photovoltaic system, as well as exploiting opportunities for low price electricity using a storage tank.

In the context of integrating electrolysis systems with renewable energy sources, the capability to operate under overload conditions emerges as a critical operational parameter. This ability not only addresses the inherent variability of renewable power sources but also offers a strategic avenue to optimize capital investment by enhancing the electrolyser's operational flexibility. The concept of overloading allows for a more dynamic response to the fluctuating supply of renewable energy, potentially leading to increased hydrogen production rates and improved economic outcomes. Park et al. [51] examined the effect of increasing the maximum overload capacity of the alkaline electrolyser from 100% (base case) to 150% on the capacity factor, hydrogen production, and economics. The results showed that allowing a maximum 150% overload significantly improved the capacity factor from 25% in the base case to 29%. This also increased the annual hydrogen production from 719 tons to 861 tons per year. The levelized cost of hydrogen (LCOH) decreased from 5.9 USD/kg to 4.8 USD/kg when the maximum overload was increased to 150%. However, the authors note that extended periods of high overload can cause stack degradation. Therefore, sensitivity analysis was done by allowing 2 hours of 150% overload followed by 1 hour of normal 100% load operation. Even with this restriction, there were still meaningful improvements in capacity factor and LCOH compared to the base case. The paper demonstrates the potential economic benefits of utilizing unused renewable curtailment by overloading the electrolyser capacity, within limits to prevent damage. The results show overloading up to 150% for durations of 2-3 hours, with breaks of 1-2 hours at normal load, can significantly increase capacity factor and annual hydrogen production while reducing the LCOH. Flamm et al. [50] conducted an analysis on the overload operation of the Siemens SILYZER 100 electrolyser. The findings reveal that each stack of the electrolyser, with a nominal power rating of 25 kW, can be temporarily overloaded to 50 kW. This overloading is governed by an internal current overload counter, which accumulates excess current over time. When the stack current surpasses the nominal 300 A, and the counter reaches 75 Ahr above the nominal, power output is restricted. Experimental results demonstrated that consistent power output restriction occurred after approximately 15 minutes of operating at 50 kW overload. The paper introduces a mixed integer linear programming (MILP) model with constraints to prevent overloading in optimization. This is crucial as power must be limited to the nominal level until the counter resets to zero. Incorporating the nonlinear overload counter dynamics into the optimization model enables more efficient operation compared to simplified power-current relations, reducing unnecessary conservatism and power restrictions. In conclusion, the Siemens SILYZER 100 electrolyser can safely sustain a 200% overload for roughly 15 minutes, and the MILP model accurately accounts for its nonlinear overload behaviour for efficient real-time operation. Rabiee et al. [52] developed a security-constrained multi-period optimal power flow (SC-MPOPF) model that incorporates the flexibility of power-to-hydrogen (P2H) units, specifically focusing on proton exchange membrane (PEM) electrolysers. These electrolysers can operate above their rated capacity for short durations, allowing for a maximum overload of 60% above their rated capacity. This means they can function at 1.6 times their normal capacity. However, this overload is limited to two consecutive 15-minute intervals, after which the electrolyser must return to its rated capacity or lower for at least two intervals before potentially overloading again. The paper demonstrated, through case studies, that permitting this temporary overloading enhances the cost-effectiveness of scheduling and extracting green hydrogen while ensuring the security of the power system. In essence, the PEM electrolysers' flexibility to sustain temporary overloads supports the integration of renewables by absorbing excess generation during peak production times. Ferrario et al. [53] conducted a study to assess the potential of power-to-gas technologies in Spain for utilizing excess electricity from renewable sources. They examined three types of electrolysis technologies: alkaline (ALK), proton exchange membrane (PEM), and reversible solid oxide cell (r-SOC). The sizing of electrolysis systems was based on the available surplus electricity from wind and solar PV plants. The paper highlights that PEM electrolysis systems can temporarily operate at 160% of their nominal power capacity, as demonstrated in a 2017 reference, but for the steady-state analysis and hourly simulations in the study, only 100% utilization of the nominal capacity was considered. No information was provided regarding overload capabilities for the ALK or r-SOC technologies. In summary, the authors evaluated different electrolysis technologies and emphasized the potential for PEM electrolysers to briefly exceed their nominal capacity by 60%, while basing their calculations and simulations on 100% utilization of the nominal capacity.

While the operational flexibility and capability to overload electrolyzers present significant advantages in the context of fluctuating renewable energy sources, these benefits are accompanied by the inherent challenge of accelerated degradation. This degradation not only impacts the performance and longevity of electrolysis cells but also introduces considerable implications for the economic viability of hydrogen production systems. Königshofer *et al.* [54] investigated the accelerated degradation of Solid oxide electrolysis cells (SOECs). Their experiment was conducted under high steam partial pressures in the feed, high steam conversions, high voltages, and low temperatures. The researchers reported that operating at low temperatures and high voltages, as well as high steam conversion rates would accelerate the degradation rates. Baldinelli et al. [55] conducted an exhaustive experimental analysis to determine the degradation impacts on solid oxide cells (SOCs) due to repeated switches between fuel cell and electrolyser modes. This investigation is critical for enhancing the durability and efficiency of SOCs, essential for energy storage and conversion systems aiming at net-zero carbon emissions. Utilizing electrochemical impedance spectroscopy and equivalent circuit modelling over a 500-hour test period, they explored the effects of commutation time and reactant gases utilization on SOC performance. The study revealed that shorter commutation times and higher reactant gases utilization rates are associated with less electrolyte resistance degradation and a pronounced increase in air electrode impedance. Commutation times in the context of the study refer to the duration of the cycle that includes both the Solid Oxide Fuel Cell (SOFC) phase and the Solid Oxide Electrolyser (SOE) phase within a complete operational cycle of a reversible Solid Oxide Cell (rSOC). Norazahar et al.[56] developed a novel reliability model for Polymer Electrolyte Membrane (PEM) electrolyzers, focusing on degradation modeling and reliability analysis due to hydrogen gas cross-over, which impacts the safety and efficiency of hydrogen production. The study employed Bayesian structural equation modeling to define causal relationships between operational variables and failure scenarios, such as membrane drying and hot spot formation. Key variables identified were current density and water quantity at the PEM's anode. The results indicated that managing these variables could significantly enhance the operational safety and reliability of PEM electrolyzers, emphasizing the importance of monitoring and controlling operational conditions to mitigate degradation risks. Shwe Sin et al. [57] investigated the impact of cation contamination on the performance of proton exchange membrane (PEM) electrolyzers and explored recovery methods to restore cell efficiency. Focusing on the degradation caused by metal cations in artificial soft water, they analyzed how these contaminants affect cell performance, including a rise in operating voltage and a decrease in hydrogen production. Their observations revealed that supplying ultrapure water and treating the membrane electrode assembly (MEA) with nitric acid could reduce the contamination effects, with the latter method being more effective in restoring hydrogen production levels. The study emphasizes the importance of addressing cation contamination in PEM electrolyzers to maintain efficiency, highlighting the potential of nitric acid treatment as a viable recovery method.

Integrating electrolyzers with renewable energy sources is a critical endeavor aimed at addressing the inherent intermittency of renewable power while forging a new pathway in the energy value chain. The rational core of this integration lies in the capability of electrolysis systems to convert fluctuating renewable energies into a stable, storable, and transportable form of energy - green hydrogen. Panigrahy et al. [58] provided an overview of different water electrolysis technologies for green hydrogen production. They discussed three main technologies - alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE). The authors explained the operational mechanisms, maturity levels, and costs associated with each technology. Alkaline electrolysis is the most mature and widely used technology but has limitations like low efficiency and purity of the hydrogen gas produced. PEM electrolysis can achieve high current densities and produce high purity hydrogen, but the cost of membranes and catalysts is high. SOE operates at 500-1000 °C, giving high efficiency, but has material degradation issues. The authors compared the capital and operational expenditures of commercial plants for the three technologies, with alkaline plants currently having the lowest cost. Overall, they concluded that reducing the cost and improving the efficiency of electrolysers, along with scaling up plant capacities, are key needs for making green hydrogen production economical and widespread. van Haersma Buma et al. [59] investigated the factors affecting technology dominance for renewable hydrogen-based electrolysis. They conducted a literature review and expert interviews to identify the most relevant factors distinguishing alkaline and proton exchange membrane (PEM) electrolysis technologies. Using the best-worst method, they then surveyed six industry experts to determine the relative importance of seven factors: price, stack size, flexibility, energy consumption, lifetime, safety, and materials used. Price, safety, and energy consumption emerged as the top three factors. The experts then evaluated the performance of PEM and alkaline technologies on each factor. With slightly higher cumulative scores, Alkaline electrolysis had a small advantage over PEM, but not enough to predict dominance. El-Shafie [60] comprehensively analysed the current state of technologies for hydrogen production from water electrolysis. The author discussed the fundamentals of the water electrolysis process and compared the main electrolyser types - alkaline, proton exchange membrane (PEM), solid oxide, and anion exchange membrane. The electrocatalyst materials for the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) in PEM and alkaline water electrolysers were reviewed, with a focus on iridium and platinum catalysts. Technical barriers when using impure water in PEM and anion exchange membrane electrolysers were investigated, particularly the impacts of cation contaminants on membrane performance. Experimental results demonstrated the effects of artificial river water contaminants on the voltage and efficiency of a commercial PEM electrolyser stack. El-Shafie concluded by evaluating challenges and future improvements needed in electrolyser membrane and catalyst materials to enhance performance and durability when utilizing impure water. Hassan et al. [61] conducted a review and comparative evaluation of green hydrogen production via water electrolysis for a sustainable and clean energy society. They discussed two main types of water electrolysis: electrochemical and photoelectrochemical (PEC). For PEC water splitting, TiO2-based nanostructured catalysts have shown superior solar-to-hydrogen (STH) efficiencies of 3.7-16.9% and photocurrent densities of 1-14 mA/cm^2. For electrochemical water splitting, non-metal catalysts like Ni-based materials exhibited excellent hydrogen evolution reaction (HER) activity, achieving overpotentials as low as 20-103 mV at 10 mA/cm^2 current density and Tafel slopes of 30-66 mV dec^{-1}. The levelized cost of hydrogen for PEC was calculated as 8.43 \$/kgH$_2$, higher than wind (4.5 \$/kgH$_2$) or solar-based PEM electrolysis (6.22 \$/kgH$_2$). Life cycle assessment showed PEC had the lowest global warming potential per kg H2 (1.0 kg CO$_2$/kgH$_2$), lower than wind PEM (4 kg CO$_2$/kgH$_2$) and solar PEM (1.5 kg CO$_2$/kgH$_2$). Nieminen, Dincer and Naterer, [62] conducted a comparative performance analysis of Proton Exchange Membrane (PEM) and Solid Oxide Steam (SOS) electrolysers, focusing on their thermodynamic characteristics, especially concerning energy and exergy efficiencies. This research is significant due to its implications for hydrogen production, a key component of the emerging hydrogen economy which aims for a sustainable and renewable energy source. They found that anodic overpotentials significantly affect both types of electrolysers, suggesting further catalyst development to reduce these overpotentials. The study revealed that increasing pressure improves the energy and exergy efficiencies of PEM electrolysers due to reduced anodic and cathodic concentration overpotentials, which in turn decreases thermodynamic irreversibility. For SOS electrolysers, they observed that energy and exergy efficiencies vary with pressure and current density, highlighting the importance of electrolytes with higher ionic conductivity at lower temperatures to improve efficiency. The research underscores the potential of enhancing electrolyser operation through temperature and pressure adjustments, along with the development of materials with better thermal and mechanical stability, to increase the efficiency of hydrogen production.

The integration of energy storage systems with electrolysis processes emerges as a pivotal strategy in the evolving landscape of renewable energy utilization and hydrogen production. This approach not only enhances the efficiency and reliability of green hydrogen production but also addresses the critical challenge of renewable energy's intermittency. By leveraging both battery storage and hydrogen as energy carriers, these systems can store excess renewable energy during peak production times and supply electricity during demand spikes or low production periods. This dual-functionality paves the way for a more resilient and flexible energy infrastructure, capable of balancing supply and demand while maximizing the use of renewable resources. Weimann *et al.*, [63] studied a wind-dominated energy system including a battery energy storage system, as well as hydrogen production both as a commodity, and a (reversible) power-to-hydrogen storage system. They developed a spatially and temporally resolved linear mixed-integer optimization program to supply electricity and hydrogen in the Netherlands. The authors concluded that the direct sale of hydrogen is economically favourable to the conversion of hydrogen to regenerate electricity if the commodity demand is available.

Ghorbani *et. al.,* [64] studied the liquefaction of hydrogen and oxygen for long-term energy storage, through the integration of wind turbines, electrolysers, and Kalina power generation cycle. The waste heat of the hydrogen liquefaction cycle was applied for power generation in a Kalina cycle, resulting in an 8.61% efficiency improvement. Ibáñez-Rioja *et al.*, [65] studied an off-grid system consisting of a 4.5 kW PEM electrolyser, photovoltaic panels, and battery energy storage. The authors reported that the electrolyser stack is the greatest contributor to the hydrogen production costs. In addition, they identified the upper bound of 0.3 €/Wh for the battery system, to become economically feasible for overnight power storage. Papadopoulos *et al.*, [66] studied hydrogen production and storage in a Belgian photovoltaic park. Various hybrid designs including integration battery energy storage and wind turbine were investigated. The authors reported that the utilization of the electrolyser system would be affected if the power is supplied only by intermittent renewable generators. In addition, the utilization factor was higher for wind power compared to solar power. However, 100% utilization can be achieved if an energy storage system is provisioned. Armijo and Philibert [67] conducted a study on flexible hydrogen (H_2) and ammonia (NH_3) production from solar and wind energy in Chile and Argentina, utilizing a techno-economic model. The locations, Chile's Atacama Desert and Patagonia, offered exceptional solar irradiance and wind resources. They optimized plant sizing and operations for minimum levelized cost, incorporating 2013 hourly solar and wind data. Assumed electrolyser efficiency was 70%, ensuring flexibility in response to renewable supply. The Haber-Bosch NH_3 synthesis process was evaluated at different operating levels. Hybridizing solar and wind resulted in marginal reductions in levelized H_2 cost (LCOH), with a maximum reduction of 1.6% in Taltal, Chile. In contrast, NH_3 production experienced more substantial cost reductions of up to 13%. H_2 storage emerged as a significant cost driver for NH_3, underlining the importance of advanced flexibility measures. The study indicates the potential competitiveness of solar-based H_2 production in Chile and wind-based NH_3 production in Patagonia compared to conventional methods. Lonis et al. [68] analysed and compared two integrated energy systems for renewable methanol production via water electrolysis and CO_2 hydrogenation. The authors developed detailed Aspen Plus process models to simulate and evaluate two configurations: one utilizing a commercially available alkaline electrolyser (AEL) coupled to a solid oxide fuel cell (SOFC), and another based on an innovative reversible solid oxide cell (RSOC) operating between solid oxide electrolyser cell (SOEC) and SOFC modes. The systems were sized for 1 MW SOFC output, with the AEL system consuming 3453 kW and the RSOC just 2528 kW. Efficiencies of 0.96 and 0.47 were calculated for the SOEC and SOFC respectively. A global efficiency of 0.339 was found for the AEL case compared to 0.332 for RSOC. While the RSOC offered significantly higher electrolysis efficiency, the overall system efficiencies were very close due to the current commercial maturity of AEL technology. The work provides a useful comparison of current and emerging technologies for power-to-methanol renewable energy storage.

Integrating electrolyzers with renewable energy sources is a critical endeavor aimed at addressing the inherent intermittency of renewable power while forging a new pathway in the energy value chain. The rational core of this integration lies in the capability of electrolysis systems to convert fluctuating renewable energies into a stable, storable, and transportable form of energy - green hydrogen. Douglas, Cruden and Infield [69] compared ambient and conventional temperature alkaline electrolyzers in terms of operational system, voltage efficiency, and corrosion rates. The focus was on integrating alkaline electrolyzers with renewable energy sources. This is important for sustainable hydrogen production. Their contribution was investigating efficiency and corrosion rates at ambient (23°C) and conventional (80°C) temperatures. Key advantages of ambient temperature are reduced auxiliary equipment, allowing dynamic operation with renewables, extended operational range, faster response time, and reduced capital and operating costs. However, conventional temperature increased efficiency by 12% for hydrogen and 19% for oxygen production but corrosion rates increased by factors of 6.3 and 2.6. Using SS-NiMo electrocatalysts in ambient electrolyzers increased efficiency by 12.4% for hydrogen while reducing corrosion rates. Overall, ambient temperature alkaline electrolyzers integrated with renewables enable reliable, efficient and cost-effective hydrogen and oxygen production. Conventional temperatures increase efficiency but accelerate corrosion, while electrocatalysts enhance ambient temperature efficiency. The authors thus demonstrated the viability of ambient alkaline electrolyzers for renewable integration, with performance improved using electrocatalysts, for sustainable and dynamic energy storage via hydrogen and oxygen. Ursua, *et al.*, [70] studied an alkaline electrolyser with a capacity of 1 Nm^3h^{-1} hydrogen production, with either a photovoltaic system of 6.8 kW or a wind turbine of 6 kW power generation capacities. They applied real data for wind speed, irradiance, and ambient temperature. The researchers identified the lower operating limit, and the number of allowed stops, as the main barriers. As the remedy, two operational strategies, namely, operating under a low load limit for a short period and battery integration were proposed. The authors reported a significant reduction in the number of stops, as well as an energy efficiency increase of 6.3% and 7.6, for integration with photovoltaic and wind systems respectively. Kojima et al. [71] comprehensively examined the challenges of utilizing fluctuating renewable energy sources like solar and wind to power water electrolysis for green hydrogen production. The authors summarized prior work characterizing the intermittent nature of photovoltaic and wind generation and strategies to smooth fluctuations by combining geographically diverse systems. They reviewed demonstrations of electrolysers driven by renewable power, highlighting the impacts of variable current, temperature, pressure, and gas purity over time on system performance and component degradation. A key finding was that start-stop cycles and reversing currents during shutdown rapidly degrade electrolyser electrodes and catalysts. The authors recommended developing new materials resistant to these operating conditions as well as standardized accelerated testing protocols to evaluate components and share results across research groups. They concluded that overcoming renewable power variability will require research into alternative operating strategies along with electrolyser designs tailored for robustness against fluctuating inputs. Ulleberg et al. [72] evaluated the performance of an autonomous wind/hydrogen energy system installed on the island of Utsira in Norway and operational since 2004. The authors analysed operational data from March 2007 to characterize the system components, including a 600 kW wind turbine, 10 Nm^3/h electrolyser, 2400 Nm^3 hydrogen storage, and 55 kW hydrogen engine. System simulations were performed using updated component models to assess alternative configurations. The work demonstrated the importance of high and steady wind resources, efficient and dynamic electrolysers, and larger hydrogen storage for 100% autonomous operation. Ulleberg et al. concluded that further improvements in electrolyser efficiency, hydrogen storage, and conversion devices are needed for wind/hydrogen systems to be cost competitive. Khouya [73] developed a simulation model of an integrated renewable energy system for hydrogen production comprising a 40 MW central receiver concentrated solar power (CSP) plant and a 10 MW concentrated photovoltaic/thermal (CPV/T) system. The CSP plant used silicon carbide particles to produce superheated steam for a Rankine cycle generating electricity. The CPV/T system also produced heat and power. A 30 MW polymer electrolyte membrane electrolyser powered by the electricity split water to produce hydrogen. The model was used to evaluate the performance of the integrated system design under the climate of Midelt, Morocco. Without storage, the simulated annual electricity and hydrogen production were 106.5 GWh and 1.87 million kg respectively, with 20% overall electrical efficiency and 34% electrolyser capacity factor. Through parametric analysis, the authors found that oversizing the solar field by a factor of 3 times the power block capacity, along with an electrolyser system of 45 MW capacity, led to the minimum hydrogen production cost of 4.07 USD/kg as well as maximized capacity factor of 100% for the integrated renewable energy system. Chen et al. [74] developed a novel hybrid proton exchange membrane fuel cell

(PEMFC) multi-generation system integrated with solar-assisted methane cracking to produce hydrogen. They established a model for the overall system, including the solar collector, methane cracking reactor, PEMFC stack and organic Rankine cycle subsystems, based on energy and exergy balances and chemical equilibrium. The influences of the solar collector temperature and product separation ratio on parameters like methane conversion, hydrogen production, subsystem outputs, efficiencies, costs and emissions were evaluated. The results showed that at 1500 K and a separation ratio of 0.6, the solar-chemical and system efficiencies reached 40.3% and 34.6%, respectively. The levelized electricity cost declined to 0.0733 $/kWh with appropriate carbon credits. For the 5 kW system over an annual operation period, the greenhouse gas emission reduction was 4×107 g and 14,556 kg of carbon was recovered. Hassan et al [75] conducted a study to compare wind and solar energy solutions for large-scale green hydrogen production through alkaline water electrolysis. They utilized a one-year experimental dataset for wind speed and solar irradiance, measured with a precision of one minute, to assess zero-carbon emissions in the process integration of hydrogen-based renewable energy. Their findings indicated that the optimal electrolyser capacity could match a 1.5 MW wind turbine power plant and a 2.0 MW solar photovoltaic power plant, producing hydrogen at varying costs depending on the energy source. The study emphasizes the potential of integrating renewable energy sources for sustainable hydrogen production, highlighting a precise methodology for evaluating and optimizing the process. This approach is adaptable for large-scale applications in industrial settings, addressing both the technical and environmental considerations essential for advancing green hydrogen as a viable energy carrier. Ursúa et al. [76] conducted a comprehensive experimental study on a 1 Nm^3/h alkaline water electrolyser, focusing on its integration with renewable energy sources, specifically wind and photovoltaic (PV) systems, for sustainable hydrogen production. The study explored the electrolyser's electrical performance, hydrogen production rate, gas purity, and energy efficiency across various operating conditions including different currents, temperatures, and pressures. Additionally, they examined the electrolyser's performance under conditions simulating standalone wind and PV energy systems. Their findings demonstrated that the electrolyser operates effectively with renewable energy sources, showing mean energy efficiencies of 77.7% for wind emulation and 78.6% for PV emulation under stable irradiance, highlighting the potential of integrating electrolysis with renewable energies for sustainable hydrogen production. Ganeshan et al. [77] developed a solar PV powered electrolyser system with a DC-DC buck converter interface to help regulate hydrogen generation. The focus of the paper is on maintaining a constant direct current through the electrolyser to achieve a uniform hydrogen flow rate, which is important for applications like hydrogen refueling stations. Their contribution is the design and testing of a current regulator circuit using the DC-DC converter to control the current supplied to the electrolyser. Key steps included: characterizing the solar PV panel and electrolyser to obtain operating parameters; finding the optimal electrolyte concentration using flow rate tests; estimating electrolyser impedance through electrochemical spectroscopy; designing the buck converter circuit; and testing the system from 440-975 W/m2 solar irradiance. Advantages of their approach include the ability to achieve regulated hydrogen production over a wide range of solar conditions. Disadvantages are that the PV system operates below peak capacity to maintain constant current, leaving potential for greater solar energy storage. Overall, the authors present a technically feasible, low-cost method for solar-powered electrolytic hydrogen generation at a uniform flow rate using a DC-DC converter as a current regulator. This could support adoption of electrolysis for renewable hydrogen production in refuelling station and related applications. Sharma et al. [78] conducted an analysis to evaluate the cost-effectiveness of different direct solar hydrogen generation (DSHG) setups, aiming to identify ways to decrease the expense of producing hydrogen from renewable sources. DSHG combines photovoltaic technology with electrocatalysis to convert sunlight directly into hydrogen within a single system. The study examined three DSHG setups: photoelectrochemical (PEC), where the catalyst is directly applied to the photovoltaic cell; coupled PV-EC, with photovoltaic and electrochemical components linked in series; and decoupled PV-EC, which incorporates a DC-DC converter between the photovoltaic and electrochemical elements. The research revealed that the decoupled PV-EC setup offered the most cost-effective hydrogen production at \$6.35/kg, in comparison to \$7.80/kg for the coupled PV-EC and \$8.90/kg for the PEC setup. This cost advantage is due to the decoupled system's higher efficiency in converting solar energy to hydrogen and the reduced need for component replacement, specifically only for the electrochemical parts. Additionally, when comparing DSHG to conventional photovoltaic-powered electrolysis, DSHG showed potential for cost competitiveness under certain conditions. A regression analysis pointed out that the lifespan and cost of membranes, gas management, and operational and maintenance expenses significantly influence the cost of hydrogen production. To meet the U.S. Department of Energy’s goal of \$2/kg for hydrogen, the study suggests concentrating on lowering membrane and system balance costs, enhancing efficiency through advanced photovoltaic cells, and choosing locations with high sunlight exposure. Nguyen et al. [79] provided an in-depth technical evaluation of large-scale direct coupled photovoltaic-electrolyser (PV-ELY) systems, examining the impact of faults, degradation, and partial shading on the performance of the PV array. It aimed to enhance energy transfer efficiency from the PV to the ELY system through two approaches: optimal sizing and optimal operation, utilizing a particle swarm optimization algorithm. Direct coupling is considered advantageous for its potential to lower both costs and system complexity compared to configurations employing DC-DC converters. However, achieving high system efficiency necessitates precise optimization of the ELY configuration. Notably, this research is distinguished by its pioneering assessment of the effects of PV faults, degradation, and shading on direct coupled systems of up to 1MW, alongside a thorough comparison of two optimization techniques. Simulation results indicated that the optimal operating strategy achieved a near-perfect coupling factor of 99.9% across all tested scenarios by dynamically adjusting the ELY configuration, whereas the optimal sizing strategy exhibited diminished performance in the face of faults and shading. Although the optimal operating method resulted in marginally higher hydrogen production, the optimal sizing strategy demonstrated superior performance during certain periods of degradation and shading. A noted limitation of the study is its reliance on simulation data without empirical validation. The detailed examination and comparison of these strategies under a range of PV conditions offer crucial insights for the design of efficient, large-scale direct coupled PV-ELY systems with enhanced hydrogen production capabilities. Dufo-López, Lujano-Rojas and Bernal-Agustín [80] focused on optimizing utility-scale green hydrogen production systems that integrate photovoltaic and wind energy sources. Their objective was to minimize the levelized cost of hydrogen (LCOH) through the use of genetic algorithms, evaluating different system types including islanded and grid-connected configurations with varying levels of electricity purchasing from the grid and considering power curtailment strategies. They conducted simulations over a 20-year system lifespan, incorporating component degradation, varying electricity prices, and renewable resource availability. Advanced modeling techniques were employed, including variable electrolyser efficiency dependent on input power and considerations for cold-start extra ageing. An example application in Zaragoza, Spain, was presented, showing LCOH results ranging from 4.74 to 16.06 euros per kilogram of hydrogen, dependent on project type and electrolyser technology. The study's innovation lies in its detailed modeling and comprehensive lifetime simulation approach, offering insights into optimizing green hydrogen production for utility-scale. Ghirardi et al. [81] developed a model to analyze the stability of power grids with high renewable energy penetration, focusing on the integration of lithium-ion batteries and hydrogen storage. They evaluated scenarios with 40%, 60%, 80%, and 100% renewable energy penetration, using photovoltaic panels and wind turbines as primary energy sources. The study highlighted the synergistic role of lithium-ion batteries and hydrogen storage in maintaining grid balance, especially for seasonal storage capabilities of hydrogen systems without self-discharge limitations. The optimal system configuration balanced renewable share against system costs, with a fully renewable system costing $0.42/kWh, where hydrogen contributed to 30% of the electric load. The findings underscore the importance of hydrogen in achieving higher renewable fractions and the economic viability of integrating hydrogen into renewable energy systems, suggesting a significant impact on future grid stability and sustainability.

Garibaldi et al. [82] developed a comprehensive model combining aero-hydrodynamic analysis with Polymer Electrolyte Membrane (PEM) electrolyzer technology to optimize offshore green hydrogen production. Aero-hydrodynamic models simulate the interactions between air and water with offshore structures, crucial for predicting the energy generation from wind and waves. This information is vital for PEM electrolyzers, which use electricity to produce hydrogen, as it enables the optimization of electrolyzer performance in fluctuating renewable energy conditions. By integrating these models, the study aims to enhance the efficiency and reliability of green hydrogen production, addressing the challenges posed by the variable nature of offshore energy sources. Kumar and Karmakar [83] designed and optimized a hybrid renewable energy system (HRES) aimed at providing electricity and hydrogen to a rural village in India, targeting both energy access and clean transportation. The paper details the selection of a village, assessment of energy needs and renewable resources, and optimization of system configurations using HOMER software. The proposed system includes solar PV (90 kW), a biogas generator (25 kW), an electrolyzer (30 kW), a hydrogen storage tank (15 kg), battery storage, and a converter, showing its economic feasibility with a net present value of Rs. 78.4 lakhs, electricity cost of Rs. 7.61/kWh, and hydrogen cost of Rs. 330/kg. The system's annual output is 250,641 kWh of electricity and 1,838 kg of hydrogen, supporting 26,000 km/year of hydrogen bus travel and reducing CO_2 emissions by 209 tonnes compared to diesel. The research highlights the dual benefits of improving local energy access and promoting clean transportation through an integrated HRES approach, emphasizing energy access, hydrogen for transportation, reduced emissions, and cost-effective system sizing. However, its applicability might be limited to specific sites, and its real-world implementation has not been demonstrated. The study offers a comprehensive method for designing HRES for electricity and hydrogen production. Martire et al. [84] conducted a study on a hybrid hydrogen thermal system at an Italian high school, utilizing solar power to generate hydrogen via alkaline electrolyzers for heating. This system stores the produced hydrogen, combining it with methane in a boiler. They created a digital model to simulate its yearly performance in two scenarios: one with photovoltaic (PV) panels fully supplying the hydrogen production, and another where electrolyzers operate only with available PV energy. By adjusting system components and hydrogen-methane mix ratios, they evaluated the system's economic efficiency. Their research aims to show the potential of using renewable hydrogen for heating in public buildings, through precise system simulation and optimization. Findings suggest a 16-year return on investment for 100% hydrogen use, assuming optimal component sizing, leading to a significant reduction of 155 tonnes in CO_2 emissions annually. The study highlights the benefits of local renewable hydrogen use and emissions reduction, despite the challenges of high initial investment and lengthy return periods. The work suggests a new method for designing and analyzing solar-hydrogen heating systems, indicating the need for financial support to enhance economic feasibility. van der Roest et al. [85] focused on the utilization of waste heat from polymer electrolyte membrane (PEM) electrolysers, a topic of significance due to its potential to enhance overall system efficiency, reduce CO_2 emissions, and improve the economic viability of hydrogen and heat production. Their investigation involved the design and analysis of different scenarios for harnessing waste heat from a 2.5 MWel PEM electrolyser, highlighting the importance of redundancy for safe operation. Through a series of case studies, including local heat use with and without a heat pump, and integration into a low-temperature district heating network, they demonstrated a potential increase in electrolyser system efficiency by 14-15% through waste heat utilization. The paper also presents a first-order techno-economic analysis, showing that the levelized costs of electrolyser heat are competitive with other industrial heat sources, with a particular sensitivity to transport distance. Makepeace et al. [86] performed an analysis to determine the feasibility of exporting green hydrogen internationally through various transport methods and routes. Green hydrogen, created from renewable sources via electrolysis, is considered a key energy carrier for reducing global carbon emissions. The study aimed to evaluate the economic aspects of transporting hydrogen in bulk across long distances, a crucial factor for the nascent hydrogen economy. The research highlighted a lack of detailed economic studies across the entire hydrogen supply chain. The authors created a framework for economic modeling to estimate costs, using MATLAB and Monte Carlo simulations for variability in critical factors such as electricity prices. This model computes the total cost of hydrogen delivery, including production, conversion, transportation, reconversion, and carbon emissions. It assesses the financial implications of various transportation methods, including ships, trucks, trains, and pipelines, and mediums like ammonia, liquid hydrogen, and Liquid Organic Hydrogen Carriers (LOHCs). The framework aims to help in making cost-effective transportation choices, although it simplifies regional and route representations. The application of this model projected the costs and trading volumes of hydrogen between major global regions for 2030 and 2050, indicating that ammonia, LOHC, or liquid hydrogen via ships might be the most economical transport options. The findings offer important perspectives on future hydrogen trade and infrastructure requirements.

The evolving landscape of water electrolysis technology, coupled with the fluctuating nature of renewable energy, presents a complex but rewarding challenge. Addressing this, a comprehensive body of research has emerged, focusing on the technoeconomic and environmental aspects of hydrogen production through water electrolysis. Oliva and Garcia [87] examined the synergistic influence of fluctuating energy prices and variable renewable generation on hydrogen production costs in diverse Chilean locations. They developed an optimization model to ascertain the optimal configuration and operation of a hydrogen plant, integrating on-site solar PV, wind generators, and electrolyser capacity, alongside grid energy utilization. Empirical data from 2018 were utilized, encompassing locational marginal prices (LMPs) and renewable generation per kW capacity for five locations. Solar and wind capacity factors ranged from 15-22% and 14-42% respectively, yielding electrolyser capacity factors of 40-92%. Key findings revealed a correlation between LMPs and renewable generation in the north, impacted by solar curtailment. The study demonstrated that employing variable prices reduced annualized cost of hydrogen (ACOH) by 13-37% for a 10,000 kg/month 100MW scale plant, with the lowest ACOH reaching US$1.15-1.35/kg. Shin et al. [88] conducted a techno-economic evaluation to determine the optimal combinations of renewable energy sources and water electrolysis technologies for cost-effective green hydrogen production. They examined three renewable power sources - offshore wind, onshore wind, and onshore photovoltaics - paired with two water electrolysis systems - alkaline (AWE) and polymer electrolyte membrane (PEMWE). Using actual renewable power generation data and modelling the efficiency of the electrolysis systems under variable input power, the authors calculated the annual hydrogen production and overall efficiency for six scenarios. By incorporating capital and operating costs, they determined the levelized cost of electricity and hydrogen in each case. Their analysis found onshore wind-AWE to have the lowest cost of hydrogen at $7.25/kg, while onshore PV-PEMWE was the most expensive option at $13.44/kg. Parra and Patel, [89] studied the techno-economics of hydrogen production using alkaline and PEM electrolysers, under the Swiss regulatory system. Assuming the opportunity for participating in wholesale natural gas, frequency, oxygen, and heat markets, they reported the levelized costs of 98.6 CHF MWht^{-1}, and the levelized value of 143.9 CHF MWht-1, with an internal rate of return of 35.1%. The authors reported that the PEM electrolyser system would have 15% levelized costs compared to the Alkaline counterpart at KW scale systems, because of the stack costs (approximately double) and decreased efficiency (increase power consumption) due to degradation near the end of life. However, for MW scale systems such difference diminishes due to economies of scale, and the reduction in the contribution of stack costs to the total costs. Matute et al. [90] developed a techno-economic model to optimize the hourly dispatch strategy for grid-connected alkaline and PEM electrolysers in the tens to hundreds of kW range. Their model incorporates multiple operating states - production, hot standby, and idle - and transitions between them, enabling cost minimization based on forecasted electricity prices. They demonstrated the model on an 80 kW alkaline electrolyser and showed savings of up to 0.8 €/kg H_2 versus a two-state model without idle, resulting from avoiding standby costs when demand is met. Through scenarios spanning electricity price variability, hydrogen demand, efficiency, and value, they found that the idle state and improved efficiency to 50 kWh/kg provided the largest economic benefits. Overall, their model provides a valuable tool to support cost-optimal operation of electrolytic hydrogen production by exploiting electricity price variations. The work quantitatively demonstrates potential savings from the multi-state approach and technology improvements. Hofrichter et al. [91] developed a methodology to determine the optimal ratio between installed renewable energy and electrolysis capacity that minimizes the levelized cost of hydrogen production. They generated load profiles for solar PV and wind energy at locations with varying renewable resources. The authors modelled electrolyser system costs and efficiency dependence on load. Using this, they calculated the levelized cost of hydrogen for renewable capacities from 0.5MW to 50MW, and electrolysis capacities from 1% to 100% of renewable capacity. The results showed the cost-optimized ratio ranged from 13.6% to 73% for PV and 3.3% to 143% for wind, depending on resource quality and capacity. The lowest cost of 2.53€/kg hydrogen was achieved with 143% electrolysis ratio for a 50MW wind farm at a high resource site. The methodology enables rapid evaluation of cost-optimal system configurations to support design and planning of green hydrogen projects. Benalcazar and Komorowska [92] conducted a rigorous techno-economic analysis of green hydrogen production in Poland through the application of a Monte Carlo simulation methodology. They examined the feasibility of cost-competitive green hydrogen production, quantifying the levelized cost of hydrogen (LCOH) for various large-scale proton exchange membrane (PEM) electrolysers (1 MW, 6 MW, and 20 MW) distributed across 17 regions in Poland. The results revealed median LCOH values ranging from €12.64-13.48/kg H_2 (solar PV) and €6.37-9.70/kg H_2 (onshore wind) in 2020, progressively declining to €1.95-2.03/kg H_2 and €1.23-1.50/kg H_2, respectively, by 2050. Notably, they identified key drivers influencing LCOH, with capital cost as the primary factor in 2020, while electricity price and utilization rate became dominant in the years 2030-2050. These findings indicate that, by 2050, renewable hydrogen could compete favourably with grey and blue hydrogen in Poland, showcasing the potential for sustainable energy transformation within a high-carbon energy system. Li et al. [93] researched capacity optimization for a utility-scale wind-photovoltaic-electrolysis-battery (WPEB) hybrid system, aiming to produce hydrogen with renewable electricity. They addressed wind and solar curtailment in Chinese provinces. China planned 13.65 GW of WPEB systems (2021-2023) to use surplus wind and solar power for hydrogen. Employing multi-constraint, single-objective optimization, they minimized the levelized cost of electricity (LCOE) for a 200 MW WPEB system in Inner Mongolia. The optimal configuration included 190 MW wind, 10 MW solar PV, 95 MW electrolyser, and 30 MW / 30 MWh battery storage, yielding a 0.2692 CNY/kWh LCOE. This setup outperformed suboptimal cases with 48-64% higher net present value and 8-33% lower LCOE. The optimal LCOE was 19-38% below 2021 Chinese wind and solar PV averages, with a competitive 10.62 CNY/kg hydrogen cost. The authors advised increasing wind-to-generation ratio, minimizing electrolyser capacity within grid sales constraints, aligning battery storage with electrolyser minimum load ratio, and ensuring ≥1-hour discharge duration. Fan et al. [94] analysed a levelized cost of hydrogen (LCOH) to compare coal-to-hydrogen with carbon capture and storage (C2HCCS) and renewable energy-powered water electrolysis for hydrogen production in China. They modelled 6 scenarios for C2HCCS based on coal price and CO_2 transport distance, finding the LCOH ranged from 13.1-19.4 RMB/kg, a 57.6-128.3% increase over coal-to-hydrogen without CCS (7.2-10.1 RMB/kg). For water electrolysis, the LCOH with coal power was 16.4-24 RMB/kg, wind power was 26.6-35.6 RMB/kg, and solar PV was 40.9-51.8 RMB/kg. Water electrolysis had higher costs than C2HCCS. Through spatial analysis, the authors found C2HCCS was most cost-effective in northwestern China. While electrolysis currently has limited competitiveness nationally, wind power in Gansu and solar PV in Chongqing showed potential. Krishnan et al. [95] integrated bottom-up and top-down costing methodologies to evaluate the present and projected costs of alkaline (AE) and proton exchange membrane (PEM) electrolyser stacks up to 2030. Their analysis aimed to offer a comprehensive understanding of cost dynamics as influenced by advancements in technology, economies of scale, and material utilization. The significance of this study lies in its contribution to the strategic planning for hydrogen production infrastructure, emphasizing cost reduction to make green hydrogen a competitive energy carrier. They observed that stack costs could potentially decrease significantly by 2030, with reductions attributed to enhanced current density, use of cheaper materials, and mass manufacturing efficiencies. The variability in PEM stack costs was highlighted, stemming from technological maturity levels. Urf Manoo et al. [96] conducted a comprehensive techno-economic analysis of seven different renewable energy systems for an educational institution in Pakistan, exploring stand-alone and grid-connected configurations involving solar, wind, and fuel cell technologies. Their work is pivotal in addressing the energy challenges faced by regions with inadequate grid access, highlighting the economic and technical viability of hybrid renewable energy systems (HRES). Through meticulous simulation and optimization using the HOMER software, they assessed the net present costs, cost of energy, and system efficiencies, ultimately determining the most economical and efficient configurations for producing 0.90079 MWh of energy per day. Their findings underscore the potential of photovoltaic, wind turbine, and fuel cell systems to provide a more cost-effective and environmentally friendly solution compared to traditional energy sources, demonstrating the feasibility of using solar and wind resources for hydrogen production and power generation. The study contributes valuable insights into the optimization of HRES for educational institutions, offering a model that can be replicated in similar geographic and climatic conditions. Reksten et al. [97] undertook a detailed examination of existing cost data and forecasts for polymer exchange membrane (PEM) and alkaline water electrolyzers (AEL), drawing on literature and manufacturer information. They crafted a cost estimation model that takes into account both the size of the plant and technological advancements. Their analysis aimed to provide more precise predictions of future capital cost reductions by including considerations of scale in addition to the year of installation, addressing a gap in earlier research which primarily focused on temporal trends without adequately considering the influence of plant capacity, especially for sizes up to 10MW. The model suggests a narrowing cost disparity between PEM and AEL by 2030, with PEM becoming more economical for capacities up to 10MW and the price per kW expected to fall to between $320 and $400 for capacities exceeding 100MW. They projected learning rates of 25-30% for both technologies, surpassing the commonly cited figures around 18%, attributing this discrepancy to the anticipation of larger plant sizes by 2030. Their work is noted for its comprehensive evaluation of cost data, the development of a nuanced cost model that merges considerations of scale and progression over time, and the emphasis on the significance of scaling in the accurate prediction of future costs and learning rates. The methodology offers a closer alignment with the dynamics influencing cost reduction, although it suggests the potential for an overestimation of PEM's learning rate due to optimistic assumptions regarding cost trends. The study underscores the necessity of integrating scale and technological advancement in forecasting future electrolyzer costs and learning rates, indicating significant potential for cost reduction, albeit with possible constraints on the rate of scale-up. Manage [98] conducted a techno-economic appraisal of different hydrogen generation technologies. The focus of the paper is examining the costs and efficiencies associated with producing hydrogen via steam methane reforming (SMR) versus water electrolysis. This comparison is important for determining the viability of transitioning to a “hydrogen economy” based on electrolytic hydrogen production rather than SMR. The authors contribute an in-depth analysis of capital and operating costs, efficiencies, and electricity prices across current and emerging hydrogen production methods. Key advantages of SMR are its commercial maturity and low costs of around $2.50/kg H2 currently. However, SMR has the disadvantage of high CO_2 emissions. Electrolyzer technologies offer reduced emissions but higher costs, with alkaline cells costing over $4/kg H2 now. High temperature solid oxide electrolyzer cells (SOECs) reach superior electrical efficiencies up to 90%, lowering operating costs. But capital costs are still high at over $700 per kW. The authors determine that SOEC systems integrated with nuclear or combined cycle gas turbine power plants, benefitting from their low electricity prices of 4-6 cents/kWh, can achieve competitively low hydrogen production costs of 5-7 cents/kWh. However, most renewable energy technologies currently have electricity costs too high to be economically viable for electrolytic hydrogen production without financial incentives. Overall, the study provides a comprehensive quantitative examination of techno-economic factors across hydrogen production methods. Kim et al. [99] studies the techno-economic and environmental feasibility of producing renewable urea using alkaline water electrolysis. Conventional urea production relies on fossil fuels, incurring high costs and carbon emissions. The authors proposed an innovative approach, utilizing hydrogen from alkaline water electrolysis coupled with captured carbon dioxide for urea synthesis via the Haber-Bosch process. They based their analysis on experimental data from the Korea Institute of Energy Research. Through Aspen Plus simulation, they assessed the performance of key components including the alkaline electrolyser, ammonia synthesis reactor, and urea synthesis reactor. Results revealed a direct correlation between increased cell potential and current density with higher hydrogen and urea production rates, underscoring the significance of the alkaline electrolyser. The economic evaluation highlighted a substantial reduction in unit urea cost from $141.88/kg at 0.18 ton/day capacity to $11.75/kg at 100 ton/day due to economies of scale. Additionally, environmental assessments indicated a global warming potential of 0.725 $kgCO_2$-eq/kg urea, primarily stemming from the energy-intensive nature of the electrolyser stack.

He et al. [100] proposed and analysed the potential of installing a seawater electrolysis system on a remote Japanese island to produce green hydrogen and sodium hypochlorite. They modelled the energy system of the island of Aguni and optimized the sizing and operation of renewable energy sources, batteries, diesel generators, fuel cells and electrolysers. Three cases were compared: Case 1 without electrolysis, Case 2 with electrolysis but no sale of chemicals, and Case 3 with sale of chemicals. Using a mixed integer linear programming approach, they minimized cost and CO_2 emissions. Compared to Case 1, Case 3 reduced costs by 16.6% and emissions by 13.2% when maximizing profit from sodium hypochlorite sales. The authors showed the economic viability of combining renewable energy powered seawater electrolysis with hydrogen storage and sales of sodium hypochlorite by-products. This provides an approach to make renewable energy systems more cost-effective on remote islands. Their model provides an optimal sizing method for hybrid systems with electrolysis. Häfele, Hauck and Dailly, [101] performed a life cycle assessment (LCA) to evaluate and compare the environmental impacts of manufacturing 1kW solid oxide electrolysis cell (SOEC) stacks with different air electrode materials (LSCF, LSCo, PrNi) and to assess impacts of high temperature electrolysis (HTE) scenarios. Manufacturing the stacks caused similar impacts across materials, with cells and interconnects being the main contributors. Including HTE showed electricity for electrolysis dominated impacts (>80%), so improving cell efficiency, lifetime and reducing degradation is key to lowering environmental impacts. Compared to a reference HTE scenario, increasing lifetime and current density decreased most impacts by 8-10%, while also reducing degradation rate lowered impacts further by ~10%. The authors highlight that cell materials and manufacturing have a relatively small but non-negligible impact and should not be disregarded. The focus on optimizing degradation, lifetime and efficiency aligns with minimizing environmental impacts. Overall, the LCA provides valuable insights on SOEC stack manufacturing and HTE scenarios to guide technology development towards improved sustainability. Mio et al. [102] developed a method to evaluate and compare hydrogen production sustainability, leveraging process simulation alongside metrics like EROEI, LCOH, and LCA, to assess various hydrogen production methods for powering medium-sized ferryboats in the Adriatic Sea. This approach, which compared green, grid, grey, and blue hydrogen, utilized Aspen Plus for process simulation to analyze energy and mass balances, efficiencies, and costs, leading to a comprehensive sustainability assessment from energy, economic, and environmental viewpoints. Green hydrogen was identified as the most favorable, with the highest EROEI and competitive cost, alongside the lowest environmental impact except for land use. This study highlights the utility of process simulation in early design stages for sustainable hydrogen system development, especially in sectors difficult to decarbonize, despite limitations in predicting actual process costs and emissions accurately. Krishnan et al. [103] conducted a forward-looking assessment of the environmental impacts of alkaline (AE) and proton exchange membrane (PEM) electrolyzer systems used in green hydrogen production, focusing on both the current and anticipated future designs. Green hydrogen is crucial for reducing carbon emissions in transportation and industry. The study assessed impacts across ten categories, from material production to operational phase. Initial findings indicated that AE and PEM systems had similar environmental impacts in their baseline designs. However, future advanced designs demonstrated improvements in most environmental categories due to higher current density, with AE and PEM maintaining similar performance levels. The study highlighted that the source of electricity and the technology of the electrolyzer stacks were the major factors affecting environmental impacts, whereas other plant components had a minor effect. When compared to traditional hydrogen production from fossil fuels, the advanced electrolyzer designs showed better performance in almost all aspects, except for the use of minerals and metals. Aghakhani et al. [104] focused on evaluating the direct carbon footprint associated with hydrogen production via Proton Exchange Membrane (PEM) and alkaline electrolyzers, using a variety of electrical energy sources and taking into account cell characteristics. They highlighted the importance of manufacturing processes and electrolyte resistance due to the high energy consumption sensitivity of PEM technology to cell voltage. The study predicted CO2 emissions for 2030 using PEM/alkaline technology in Italy and anticipated an 18% reduction in national electricity grid CO_2 emissions in Australia by 2030 compared to 2019. Through experimental data, they found that energy consumption for hydrogen production using PEM technology is more sensitive to cell voltage than to current density, emphasizing the significance of cell manufacturing and electrolyte resistance. Additionally, a sensitivity analysis on energy sources indicated that carbon dioxide emission in Australia is more sensitive to renewable energy sources than in Italy.

Abu et al. [105] conducted a comprehensive analysis of electrolyser control technologies for hydrogen production through patent landscape analysis and technological updates. They aimed to understand current research and patent trends in hydrogen electrolyser technologies, important for facilitating the clean energy transition. By performing keyword searches in the Lens database, they selected 107 patent publications for analysis, providing insights into patent growth, key players, jurisdictional distribution, and technological sectors. The study highlights the significant growth in patent applications over time, emphasizing the increasing focus on renewable energy and decarbonization efforts. Emerging technologies identified include Solid

Polymer Electrolyte Electrolysis, Photoelectrochemical water splitting, Microbial electrolysis, and High-Temperature Electrolysis, each contributing to the efficiency and sustainability of hydrogen production. Leading research frontiers focus on the integration of renewable energy sources with electrolyser technologies, advancing materials and system designs, and exploring new applications for hydrogen energy.

Salehmin et al. [106] conducted a comprehensive review on the challenges and advancements in high-pressure Proton Exchange Membrane (PEM) water electrolysers, focusing on their potential for green and low-cost hydrogen production. They identified that while high-pressure PEM electrolysers offer significant benefits in reducing total power consumption and thereby the costs associated with hydrogen production, they also face numerous technological and operational challenges that hinder their broader commercialization. The paper discusses the benefits of high-pressure operation, such as increased gas purity and reduced need for external compression, alongside the drawbacks, including gas crossover, component degradation, and safety issues. They provided a detailed discussion on diffusion, ohmic, and activation losses; gas permeation/crossover; and the degradation of components and materials, offering solutions and mitigation strategies. Importantly, the review highlighted the need for further research and development to enhance the efficiency, durability, and cost-effectiveness of high-pressure PEM electrolysers, emphasizing their crucial role in the transition towards sustainable energy systems.

Arsad et al. [107] conducted a comprehensive review and analysis of hydrogen electrolyser technologies, emphasizing their critical role in sustainable energy production. They explored the advancements in electrolysis methods for hydrogen production, underscoring its significance as a sustainable and high-purity approach. The focus was on detailing the current state of water electrolysis technology, modeling with renewable energy sources, and addressing challenges like electrolysis techniques, capital costs, water consumption, rare material utilization, efficiency, environmental impact, and storage and security implications. Through their analysis, the authors aimed to identify current control methods for efficiency improvement to reduce costs, increase lifetime, and enhance performance within a low-carbon energy system. Their observations revealed qualified promise in hydrogen's role across various applications, with a call for more research and development to advance hydrogen electrolyser technologies towards achieving clean, sustainable, and green energy solutions.

Alsunousi and Kayabasi [108] examined the role of hydrogen (H_2) in the production of synthetic fuels, addressing its significance in reducing carbon emissions and its impact on global warming and the economy. Their focus was on the interplay between H_2, carbon emissions, energy efficiency, and the potential of renewable energy sources. They discussed carbon reduction methods, including various carbon capture technologies, and highlighted the importance of H_2 as a cornerstone in developing synthetic fuels and future energy systems. Observations revealed that despite the potential of renewable energy sources to reduce CO_2 emissions, the discontinuity and storage challenges limit their impact. The paper detailed the production processes of synthetic fuels, like the Fischer-Tropsch and Haber-Bosch processes, and methanol production, emphasizing the environmental and economic benefits of integrating H_2 from renewable sources. It concluded that sustainable H_2 production techniques are crucial for low-carbon fuel production, suggesting that advancements in renewable energy integration and carbon capture technologies are essential for a sustainable future. The study's results indicated that synthetic fuel production, particularly through the combination of H_2 and captured CO_2, presents a promising path for reducing fossil fuel consumption and addressing renewable energy storage challenges.

Arsad, Hannan, Al-Shetwi, Hossain, et al. [109] presented a comprehensive bibliometric analysis of research on hydrogen electrolysers utilizing the Scopus database to highlight trends, challenges, and future research directions in this field. The authors focused on examining the most cited studies related to hydrogen electrolysers for sustainable and efficient energy production, aiming to provide insights into historical evolution, current updates, and trends. The analysis identified key research topics, including the formulation of problems and simulations, state-of-the-art technology assessment, laboratory research design, performance evaluation, and review articles. It revealed a significant emphasis on controlling hydrogen electrolyser efficiency, with a considerable portion of articles addressing this aspect. The study underscores the importance of hydrogen electrolysers in achieving sustainable energy production, highlighting the challenges faced by researchers, such as unpredictable and fluctuating electricity generation from renewable sources, modelling constraints, high investment and operating costs, and storage and safety concerns. The findings suggest a growing research interest in hydrogen electrolysers, reflecting their potential in facilitating the transition to a sustainable energy system.

Modu et al. [110] conducted a systematic review on hybrid renewable energy systems (HRES) with hydrogen storage, focusing on sizing optimization and energy management strategies (EMS). They highlighted the importance of efficient energy storage in managing intermittent energy supply from renewable sources. The paper provides a comprehensive analysis of current advancements in sizing and EMS for HRES, emphasizing the potential of hydrogen-based storage as a superior alternative to batteries due to its larger size, longer lifespan, and higher efficiency. Through a detailed literature review, the authors explored various optimization techniques, including classical and artificial intelligence methods, and discussed the application of different software tools for HRES analysis. They examined energy management strategies considering demand fulfillment and technical-economic decision issues. The paper concludes with a synthesis of major findings, stressing the critical role of hydrogen storage in enhancing the reliability and performance of HRES.

Edwards et al. [111] conducted a comprehensive review on the challenges and advancements in 3D computational fluid dynamics (CFD) modelling of proton exchange membrane fuel cells (PEMFCs), focusing on the accuracy and time efficiency of these models. They addressed the complexities in designing and utilizing these models due to the intricate electrochemistry, significant variations in component scales, and the lack of experimentally known input parameters. Through a meticulous examination of numerical methods, meshing strategies, assumptions, simplifications, required inputs, and validation methods, they presented an extensive analysis of current literature findings. Their observations highlighted shortcomings in common modeling assumptions and introduced innovative validation methods and meshing techniques. They also identified knowledge gaps in model numerical methods and input parameters, providing several recommendations for future research. The paper emphasizes the importance of accurate and efficient CFD modeling in improving the understanding and development of PEMFCs, which are promising for their efficiency and emission-free operation but still face hurdles towards widespread commercial adoption.

Guo, Zhu and Zhang [112] offered an industrial viewpoint on electrolyser technology and hydrogen production, examining the current status of four primary water electrolysis methods: alkaline (ALK), proton exchange membrane (PEM), anion exchange membrane (AEM), and solid oxide (SOEC). They outlined each technology's development, challenges, and industrial applications. ALK is identified as the most established but has limitations in efficiency; PEM addresses these limitations at a higher cost due to expensive materials; AEM aims to merge PEM and ALK benefits but faces issues with membrane performance and durability; and SOEC, while efficient, is hindered by material durability. The study notes that ALK and PEM are prevalent in industrial settings. It also covers the design considerations and configurations for power supplies that convert renewable energy for electrolysis, with an emphasis on the use of multi-pulse thyristor rectifiers in AC/DC converters for their efficiency and reliability, though noting existing limitations in power quality and density that require further improvement.

Shahril et al. [113] presented a review of the dynamic responses of unitized regenerative proton exchange membrane fuel cells (URPEMFCs) during operational and transient states. URPEMFCs can function as both a fuel cell to produce electricity and as a water electrolyzer to regenerate hydrogen and oxygen gases. The focus of the review was on the parametric responses related to cell durability and performance during operation and mode changes between fuel cell and electrolysis modes. This is an important area of research because the additional functionality of URPEMFCs makes them more sensitive to changes compared to conventional fuel cells. The key parameters examined were water and temperature management.

Together, these reviews paint a comprehensive picture of the field's current landscape, underscoring the critical role of hydrogen production through water electrolysis in the transition to a sustainable energy system. They highlight the importance of technological advancements, integration with renewable energy sources, and overcoming operational and environmental challenges. This collective body of work provides a valuable roadmap for future research and development efforts aimed at unlocking the full potential of water electrolysis in the global pursuit of clean, sustainable, and efficient hydrogen production.

Upon the critical review presented in this section, it is clear that the flexible operation of electrolyser systems has significant implications for the economic viability of green hydrogen production from intermittent renewable energy systems. However, most of these studies focus on either the design of electrolyser systems, or the transient performance of a specific stack. It is not well understood how different operational strategies will affect the performance of electrolyser systems with multiple stacks. How these designs are operated when they are powered by intermittent energy systems will impact their performance, and needs to be understood. Therefore, the present study is devoted to quantitatively exploring the economic impact of various alternative operational strategies for green hydrogen production from wind energy. The key novelties and contributions of the present research can be summarized as:

- Develops an optimization model to assess flexible operational strategies for electrolysers integrating with intermittent renewable power.
- Quantitatively analyses economic trade-offs between electrolyser shutdown strategies, overloading capacities, and battery integration.
- Identifies optimal operational regimes balancing efficiency, flexibility, and system economics.
- Compares alkaline and PEM electrolyser technologies under flexible operation strategies.

- Provides insights on integrating electrolysis with renewable power to optimize techno-economics.

The present research extends the work originally developed in Cooper, *et al.* [40] by investigating how various design and operational choices impact the levelized cost of hydrogen (LCOH). It seeks to understand the impact of different stack shutdown strategies, stack overloading, and the potential benefits from battery integration.

The present section provided an introduction and put the research in context. The next section presents the research question by articulating the problem statements of interest. The next section provides the representation of the research problems through mathematical programming. In Section 4, the modelling data applied for the construction of the case studies are presented. Section 5 presents and discusses the result. Finally, the paper concludes by summarising key research findings.

2. Problem Statement

The present research incorporates the findings from open literature in the form of equipment performance, technical considerations, and costs into an optimization-based decision-support program. The developed model was then applied to evaluate various operational strategies of the electrolyser system. Four key problems were investigated:

Problem 1. What should the operational strategy for partial shut-down and near-minimum load operation be to minimize the levelized cost of hydrogen (LCOH)?

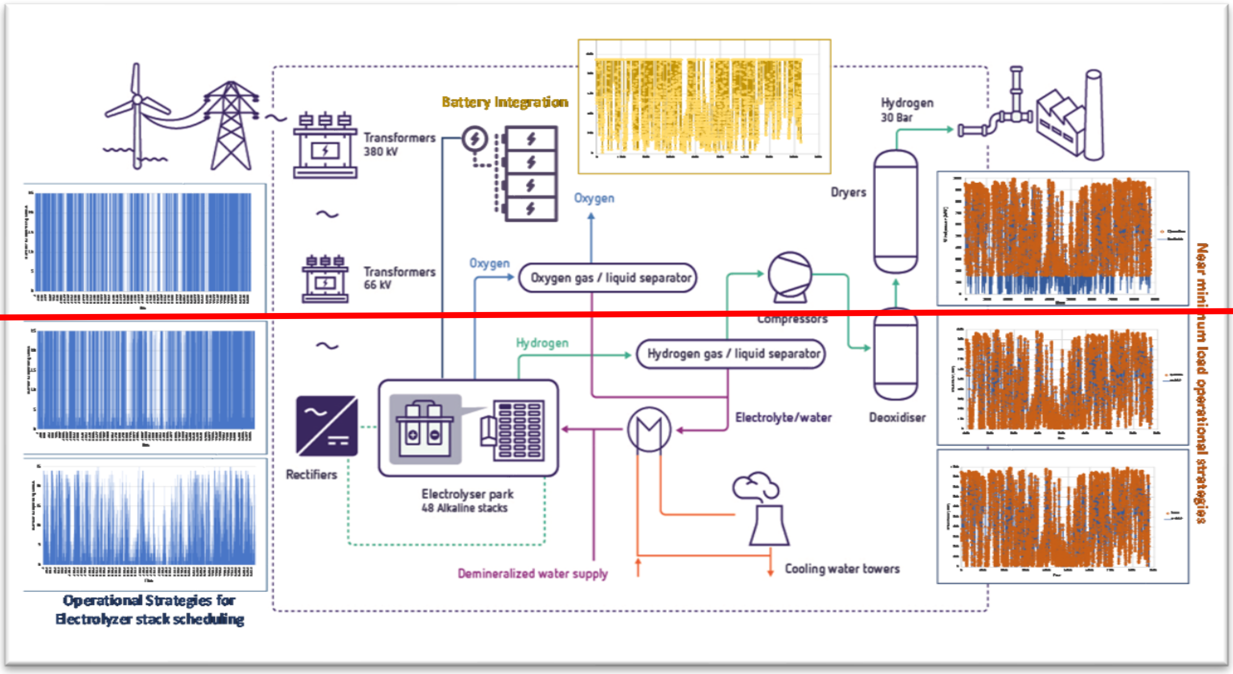
Problem 2. Is it possible to overload the electrolysers for a short period of time and does it result in improved LCOH through reduced stack size?

Problem 3. Can integration of a battery energy storage system (BESS) with the electrolysers reduce the levelized cost of hydrogen?

Problem 4. What is the economic implication of volatility in electricity price, and can it be exploited for lowering the levelized cost of hydrogen?

In the following, the general mathematical formulation of the model is presented first. Then, this formulation is modified in order to construct the required mathematical representations to explore the abovementioned Problems 1-4.

The case study diagram illustrated in **Fig. 1**, shows the innovative integration of renewable wind energy into the electrolysis system, aiming to optimize hydrogen production. At the core is the "Electrolyser Park" consisting of Alkaline or PEM stacks, directly powered by wind energy that undergoes voltage transformation. Essential system components include oxygen and hydrogen separators, demineralized water supply, and rectifiers. Furthermore, battery integration ensures consistent energy supply, while the multiple data plots offer a deep dive into the system's performance metrics over time.



~~**Fig. 1.** Integrated Renewable Electrolysis System: Harnessing Wind Energy for Optimized Hydrogen and Oxygen Production (adopted and modified from [114])~~

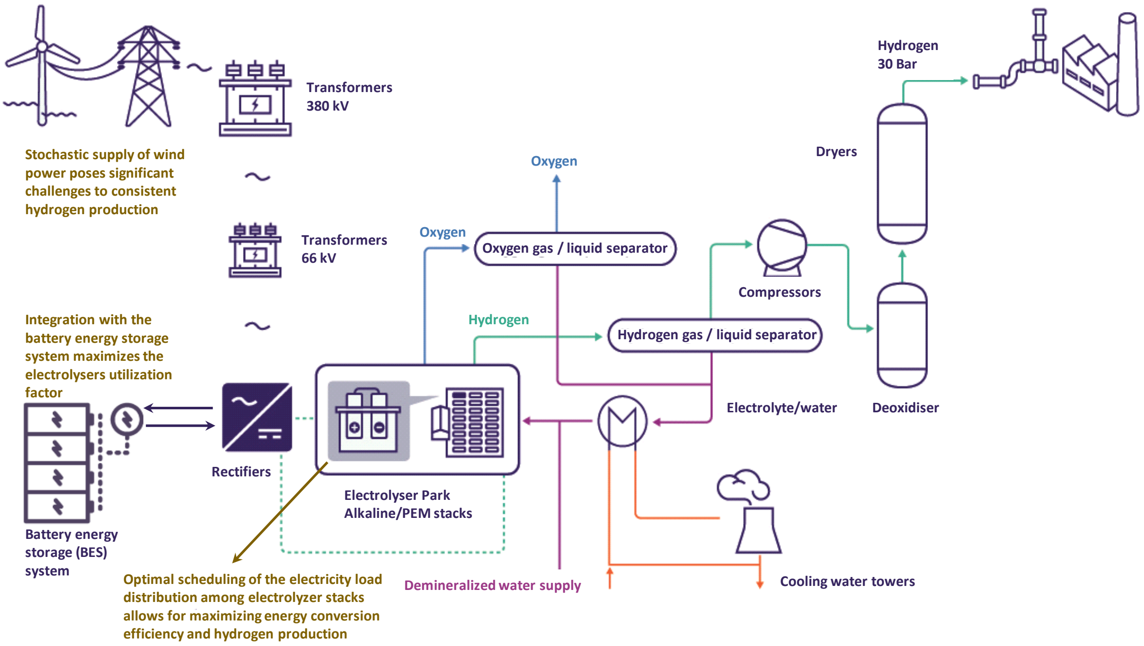


Fig. 1. Schematic of an Integrated Wind-Energy-to-Hydrogen Production Facility: This diagram illustrates the conversion of variable wind power into stable hydrogen production via electrolysis, incorporating battery energy storage and optimal stack load scheduling for enhanced efficiency.

3. Mathematical formulation of optimization problems

The mathematical formulation of the optimization problem was originally adopted from [40]. The objective is to minimize the levelized cost of hydrogen subject to constraints concerning the performance of process equipment and associate technical limitations, as well as the constraints representing the economic model of the whole system, as discussed extensively in **Supplementary Materials (SM)**, and concisely shown in the following.

Objective function:

Minimize the levelized cost of hydrogen (LCOH)

subject to constraints concerning:

economic model (capital and operating costs): ***Eq. S1-S8*** in ***SM***

selection of operating blocks (consisting of multiple electrolyser stacks) ***Eq. S9-S13*** in ***SM***

the performance of the electrolysers and balance of plant (BoP) in converting electricity to hydrogen ***Eq. S14-S23, Eq. S25*** in ***SM***

the availability of wind power ***Eq. S24*** in ***SM***

This base mixed-integer linear programming (MILP) model, described fully in the Supplementary Materials, provides a general optimization framework for minimizing the levelized cost of hydrogen production from an electrolyser system. The model incorporates constraints on the system economics, equipment performance, selection of operating blocks, conversion of electricity to hydrogen, and availability of renewable electricity. This work then adapts the base model by modifying existing constraints or incorporating additional ones in order to analyse the specific research problems of interest, as detailed in the following subsections. In order to construct the mathematical representation of Problems 1-4, additional constraints are included, or the existing constraints were modified as discussed in the following.

3.1. Problem 1. Investigating shut-down strategies for near-minimum load operations

The electrolyser system encounters various technical limitations when the demand for hydrogen or the availability of electricity reaches their lower bounds. At low operational levels, gas crossover across the membrane increases significantly, which is an explosion danger for the system. Further, corrosion issues can be exacerbated at low loads, degrading the stacks more rapidly. For these reasons, the cells are restricted to only operate above a specific minimum load limit. The technical limitation of the electrolyser cells is reported to be 10% and 15% for PEM and Alkaline technologies, respectively [115]. However, more stringent constraints are imposed on the balance of plant (BoP) side. For example, when the compressors used in this work are operated below 25% of the nominal load, they enter a recirculation mode, where the power consumption of the compressors remains almost constant. Therefore, as the load diminishes, the unit cost of hydrogen production escalates, indicating the existence of an economic threshold for hydrogen production that must be delineated through optimization. In these designs, the Alkaline system uses four compressors, which translates into a minimum of 6.25% of the nominal H_2 production rate. The PEM technology operates at an elevated pressure that does not require compressors. There are three considerations concerning shut-down strategies for near-minimum load operations, and their combination would result in different operational strategies:

Load Distribution: the electricity load can be distributed evenly over the stacks, which results in ease of operation, as well as more predictability and tractability of operation. However, if the electricity load of each stack is decided independently, additional degrees of freedom become available for operational optimization.

The number of operating stacks: keeping the minimum number of stacks operational at any given time slows the aging of the overall system and facilitates maintenance procedures. However, it limits the system flexibility and also forces the individual stacks to operate at higher loads, which lowers their efficiency [116].

Shut-off strategy: various stack shutdown strategies could be planned, for example by switching all the stacks off *at* a critical load, allowing their shut-off *after* a certain load, or allowing their shut-off *at any* load.

To enable analysing different shutdown strategies for near-minimum load operation, several new constraints were added to the base model:

- Constraints to distribute load evenly across all electrolyser blocks, or allow independent optimization of each block's loading level. This impacts operational ease versus flexibility.
- Constraints setting minimum load levels for the overall system and individual blocks. Lower minimum loads increase flexibility but may raise technical limitations.
- Conditional constraints controlling when individual blocks can be shut down - for example, allowing shutdown only after the whole system reaches a minimum load, versus allowing shutdown of individual blocks at any loading condition. The shutdown constraints significantly impact flexibility

Incorporating the above considerations in the present research, three operational strategies were investigated through the following subproblems:

Subproblem 1.1. All electrolyser blocks have equal loading, regardless of the system power level. Stacks have a minimum load of 15% for Alkaline, 10% for PEM, and, as a result of equal loading, either all of them are shut down or none. To elaborate, the entire system ceases operation when the system power level descends to 15% for Alkaline technology (or 10% for PEM technology).

Subproblem 1.2 All electrolyser blocks are independent of one another regardless of the system power level. However individual blocks can be shut down only once the entire system has reached 15% load for the Alkaline system (or 10% for the PEM system). Electrolyser blocks will be shut off as soon as possible once they reach the system-wide critical level. Thus, this operational strategy aims to maintain the minimum feasible number of stacks below the critical load threshold to maximize the average load across electrolyser blocks. For the case of Alkaline technology, a constraint regarding the minimum compressor power (6.25% H_2 production rate) will apply to the balance of plant (BoP). The recirculation mode is modelled by maintaining the BoP power requirement at a constant value.

Subproblem 1.3. All electrolyser blocks are independent of one another, regardless of the system power level. Electrolyser blocks have a minimum load of 15% for Alkaline, 10% for PEM. Electrolyser blocks can be shut down at any system load. Electrolyser blocks will be shut off as soon as possible to keep the minimum number of operating electrolyser blocks operational i.e., the average load of electrolyser blocks is kept as high as possible. Similarly, a constraint regarding the minimum compressor power (6.25% H_2 production rate) will apply to the balance of plant (BoP), as it enters the recirculation mode, but not for the PEM system.

The mathematical formulations of the above three problems are presented in the following.

3.1.1. Even distribution of the electrolyser load

The constraint forcing equal load distribution reduces operational flexibility by requiring all blocks to be on or off simultaneously. However, it provides simplicity of operation and control. The mathematical presentation of **Problem 1.1** includes the following constraints which ensure the electricity load is distributed evenly over all the electrolyser blocks:

$$Power_{block}(i,k,t) = Power_{block}(i-1,k,t) \qquad \text{Eq. 1}$$

$Power_{block}(i,k,t)$ is power loading level (MW) for a specific block number, and technology at any given time.

In addition, the following conditional constraints force all the blocks to shut down after the minimum load is reached:

If

$$\sum_{e} Elec_{avail}(t,e) < \ minLoad \times blockCap(k) \times numBlocks \qquad \text{Eq. 2}$$

Then:

$$Power_{block}(i,k,t) = 0 \qquad \text{Eq. 3}$$

Where $Elec_{avail}(t,e)$ is the available electricity (MW) at any time in any price tier, and $numBlocks$ refers to the number of electrolyser blocks. $minLoad$ refers to the selected system-wide minimum load (a sensitivity variable), and $blockCap(k)$ is the power capacity for electrolyser blocks which depends on the selected technology.

3.1.2. Independent optimization of the electrolyser load above the critical load

Allowing independent optimization of each block's loading level above the minimum system load provides more flexibility in operation. However, restricting shutdown to only occur after the overall system load drops below a critical level helps maintain high average stack loading. The mathematical presentation of **Problem 1.2** includes the following constraints:

If

$$\sum_{e} Elec_{avail}(t,e) < minLoad \times blockCap(k) \times numBlocks \qquad \text{Eq. 4}$$

Then:

$$\sum_{i} Power_{block}(i,k,t) > \sum_{i} O(i,k,t) \times blockCap(k) \qquad \text{Eq. 5}$$

where $O(j,t)$ is a Boolean variable that represents the operational status of an electrolyser block (value one for in-operation status, and zero for shut-off). Eqs. 4 and 5 ensure that after the system-wide minimum load, the minimum number of cells are in operation.

3.1.3. Maintaining a minimum number of electrolysers operational

Allowing fully independent operation and shutdown of each electrolyser block provides maximum flexibility. However, this risks lowering the average stack loading since blocks can be shut down at any system load. For **Problem 1.3**, the constraint in Eqs. 4 and 5 is enforced at any load:

$$\sum_{i} Power_{block}(i,k,t) > \sum_{i} O(i,k,t) \times blockCap(k) \qquad \text{Eq. 6}$$

3.2. Overloading the electrolyser blocks

To model overloading scenarios, the allowable operating range constraints were adapted by expanding the upper limit beyond original equipment specifications. This represents potential technical improvements that would allow temporary overloading to optimize utilization and economics. In **Problem 2**, the potential for overloading the electrolyser cells for short operational durations was evaluated from an economic point of view. More recent technological developments indicate that such an operational strategy might be technically feasible. For instance, SILYZER 100 electrolysers developed by Siemens has a nominal power of 25 kW, but can tolerate power loads up to 50 kW for the short duration of 15 minutes. While the technical risk of overloading is subjective and different vendors reported different values, it is clear that overloading electrolyser cells for long durations would accelerate the aging and degradation phenomena. It is still valuable to estimate the economic gains that can be achieved through the overload operation, as this would present the opportunity to ‘undersize’ stacks, providing savings in capital costs. The scenarios considered in the analysis of operational strategy in Problem 2, also included parametric exploration of system minimum load, in order to quantify the highest economic impact.

As will be discussed in **Result Section**, the operational strategy presented in **Problem 1.2** offers the lowest (best) levelized cost of hydrogen (LCOH). Therefore, for the sake of brevity and in order to manage the computational costs, overloading studies were only conducted for this operational strategy. Therefore, the mathematical formulation of **Problem 2** was constructed based on the mathematical formulation of **Problem 1.2** by reducing the number of the electrolyser blocks to about 90% of the original capacity, and giving the blocks a greater operational range than the originals.

3.3. Integration with a battery energy storage system

Integrating battery energy storage into the base model required adding new constraints to represent the storage system itself, including limits on the charge/discharge rates and conservation of energy within the batteries. The overall system energy balance constraint was also modified to account for storage charging and discharging. These additions enable analysing the potential benefits of battery integration. In **Problem 3**, the possibility of the utilization of battery energy storage (BES) was considered. Integrating the electrolyser system with energy storage offers multiple advantages including an increase in asset utilization, an increase in the efficiency of stacks by tuning the load of electrolysers, and potentially utilizing temporal arbitrage in the electricity price.

The charging and discharging sign convention is:

- A positive value of $EnergyStorageChange$ represents discharging the energy storage system
- A negative value of $EnergyStorageChange$ represents charging the energy storage system

With the above consideration, the mathematical formulation of Problem 3 includes the following constraints.

The equality constraint in Eq. 7 establishes the relationship between energy and power storage change:

$$EnergyStorageChange(t) = \Delta t \times PowerStorageChange(t) \qquad \text{Eq. 7}$$

Where Δt is the time interval. $EnergyStorageChange(t)$ and $PowerStorageChange(t)$ represent the changes in the energy and power stored in the battery system, respectively.

Over the time horizon, no net accumulation of power should occur

$$EnergyStorageChange(initial(t)) = EnergyStorageChange(end(t)) \qquad \text{Eq. 5}$$

where $initial(t)$ and $end(t)$ refer to the beginning and end of the time horizon, respectively.
There are upper and lower limits on the total charge of the battery energy storage (BES) system:

$$StoredEnergy(t) < BattSysCap \qquad \text{Eq. 6}$$
$$StoredEnergy(t) > 0 \qquad \text{Eq. 7}$$

In Eq. 6, $StoredEnergy(t)$ represent the state of charge of the battery, $BattSysCap$ is a design parameter concerning the capacity of the battery system.
There are also upper and lower limits for the rate of charge or discharge of the batteries:

$$EnergyStorageChange(t) < MaxChargeRate \qquad \text{Eq. 8}$$
$$EnergyStorageChange(t) > MaxDischargeRate \qquad \text{Eq. 9}$$

There is a constraint regarding the conservation of energy on the battery energy storage system.

$$StoredEnergy(t) = -EnergyStorageChange(t) + StoredEnergy(t-1) \qquad \text{Eq. 10}$$

Integrating the battery energy storage (BES) system also alters the energy balance in the system. Therefore, Eq. S15 in SM is replaced by Eq. 11.

$$\begin{aligned} BattEff \times PowerStorageChange(t) + \sum_e ECE(t,e) \\ = \sum_i [Power_{block}(i,k,t) + sBoPElec(k)] \end{aligned} \qquad \text{Eq. 11}$$

$BattEff$ is the energy conversion efficiency during charging and discharging the battery system. ECE is the electricity consumed in any tier in any given time period (MW). $sBoPElec$ is the specific electricity consumption for the balance of the plant, which also depend of the selected technology.
Considering the capital and operating costs of the battery energy storage system, the constraint describing the capital costs of the whole system Eq. S5, is modified as follows:

$$\begin{aligned} TotalCost = \sum_t \frac{OpntExpnc(t)}{1000} + CCF \times (CaptlExpnc + BatteryCaptlExpnc) \\ + gridFee + OpMain + OpMainBatt + Rep + LandWater \end{aligned} \qquad \text{Eq. 12}$$

Where $BatteryCaptlExpnc$ and $OpMainBatt$ are the capital and operating costs of the battery energy storage system, respectively.

3.4. Temporal arbitrage of the volatilities in the electricity price

To evaluate the impact of electricity price volatility, the price inputs to the base model were modified to generate a range of variability scenarios. This enables quantifying potential economic gains from arbitraging price differentials. In **Problem 4**, an attempt was made to quantify the economic impact of temporal differentials in electricity prices. Here, the model developed in Section 3.3 was further developed by considering different values for electricity tier prices. The motivation for the temporal arbitrage in the electricity price is to purchase and store electricity when the price is low and to provide electricity from storage when the price is high. The ultimate objective is to minimize the levelized cost of hydrogen by maximizing the utilization of the electrolyser stacks while minimizing average electricity price.

A normal distribution was assumed for the electricity price and the standard deviation varied from 30 to 70% of the average electricity price. A new price was generated using this price distribution for each time unit of the time horizon, which in this case was every hour. Using this method, three different price volatilities were explored, with standard deviations of 30%, 50%, and 70%, relative the baseline condition of a fixed price.

In summary, the base MILP model provides a general optimization framework that is tailored for each research problem through adapting constraints to represent the particular equipment configurations and operational strategies of interest. The added or modified constraints enable analysing flexible shutdown approaches, overloading scenarios, battery integration benefits, and exploiting electricity price volatility to minimize the levelized cost of hydrogen production.

4. Modelling data

The modelling data was adopted from open literature and is listed in Tables 1 and 2. For both alkaline and PEM electrolysers, baseline and advanced designs are considered to present the current state of the art, and literature-based predictions for the technological state of art in a foreseeable future (*e.g.,* 2030). The performance information regarding the alkaline baseline technology and advanced technologies were taken from [117] and [118], respectively, and is shown in **Fig. 2.a.** and **2.b.** The performance information regarding PEM baseline technology was adopted from [119,120] and the information regarding the performance of the advanced technology, was adopted from [121], as shown in **Fig. 3.a.** and **3.b.**, respectively. The features of interest include the polarization curves, as well as the Hydrogen Production Rate as a function of Power to Stack. While the relationship between the Specific Energy Consumption and the Electricity Load is highly nonlinear, the relationship between the Hydrogen Production

Rate and the Power to Stack is fairly linear which offers the opportunity to simplify the model while ensuring the fidelity of results. The data for the battery for both baseline and advanced scenarios, was adopted from a recent report by NREL [122]. Economic data was adopted from [123] and [114], for baseline and advanced scenarios respectively.

It should be noted that the polarization curves for the advanced versions of each technology are sourced from papers which examine potential improvements to each technology. For the advanced AWE technology, Jang *et al*., [118] examined a zero-gap type electrolysis cell which uses nickel-foam electrodes on both sides of the diaphragm. This type of electrolyser can reduce both reactant transport distances, and the contact resistance from the transport of electrons, improving the overall performance. However, these designs are not yet commercialized at large scale, and so they are considered 'advanced' design. For the advanced PEM design, Siracusano *et al.*, [121] investigated the impact of catalyst design choices on performance. They found that exotic catalysts with alternative chemical morphologies & physical deposition mechanisms reduce the activation energy for the oxygen evolution reaction, significantly improving performance. As these catalysts are not currently used in PEM electrolysers, they are considered 'advanced' designs for this work.

Due to the granularity of our analysis, which was conducted with a 1-hour temporal resolution, the slight differences in ramp rates between PEM and alkaline electrolyzers were not discernible, leading to an identical ramp rate assignment for both technologies in our study. This methodological choice was made to balance the detail of our analysis with the computational demands of incorporating a full year's data to accurately reflect seasonal variations in wind power generation.

The problem was formulated as a mixed integer linear program and was solved using IBM ILOG CPLEX 32.2.0 at GAMS platform. The size of the problem was in the order of 2.4×10^6 - 4.2×10^6 constraints and 9×10^5 - 1.7×10^6 variables from which 2.3×10^5 - 4.2×10^5 were discrete variables.

Table 1. The electrolyser and economics parameters, and considerations applied in the modelling of the baseline and advanced designs for Alkaline Technology

Baseline Design for Alkaline Technology		
Technology	Alkaline	
Total system capacity	990	MW
Critical Load (for each block)	15	%
lifetime of plant	15	Years
Discount rate	8	%
OpMain	13.24	The annual operations maintenance costs (2% of direct costs) million Euros
Rep	18.25	The annual stack replacement costs (10% direct stack costs) – million Euros
LandWater	5	The cost of land lease and water supply – million Euros
CapEx (2020 cost level)	1411	The capital investment cost - million Euros
gridFee	24	The annual grid fees - million Euros
Number of cells in a stack	230	#
Number of stacks	432	#
stack per block	8	#
block capacity	18	MW/block
Number of blocks	54	#
rampRate	600	The rate at which block can vary - percent per hour
Compressors per block	4	#
Compressor min load	25	%
Balance of Plant (BoP) min load	6.25	%
BatteryCapex	207	capital investment for the battery system – million Euros
Charge/Discharge rate	4	Hours (i.e., 25% capacity per hour)
Battery Energy Storage efficiency	90	%
Transformer-Rectifier losses	3.7-5.2	%

Advanced Design for Alkaline Technology		
Technology	Alkaline	
Total system capacity	989	MW
Critical Load (for each block)	15	%
lifetime of plant	15	Years
Discount rate	8	%
OpMain	8.4	The annual operations maintenance costs (2% of direct costs) – million Euros
Rep	10	The annual stack replacement costs (10% direct stack costs) – million Euros
LandWater	5	The cost of land lease and water supply – million Euros
CapEx (2020 cost level)	730	The capital investment cost - million Euros
gridFee	24	The annual grid fees - million Euros
Number of cells in a stack	232	#
Number of stacks	96	#
stack per block	8	#
block capacity	82	MW
Number of blocks	12	#
rampRate	600	The rate at which block can vary - percent per hour
Compressors per block	4	#
Compressor min load	25	%
BoP min load	6.25	%
BatteryCapex	207	capital investment for the battery system – million Euros
Charge/Discharge rate	4	Hours (i.e., 25% capacity per hour)
Battery Energy Storage efficiency	90	%
Transformer-Rectifier losses	3.7-5.2	%

Table 2. The electrolyser and economics parameters, and considerations applied in the modelling of the baseline and advanced designs for PEM Technology

Baseline Design for PEM Technology				**Advanced Design for PEM Technology**		
Technology	PEM			**Technology**	PEM	
Total system capacity	989	MW		**Total system capacity**	989	MW
Critical Load (for each block)	10	%		**Critical Load (for each block)**	10	%
lifetime of plant	15	Years		**lifetime of plant**	15	Years
Discount rate	8	%		**Discount rate**	8	%
OpMain	19.925	The annual operations maintenance costs (2% of direct costs) – million Euros		**OpMain**	9	The annual operations maintenance costs (2% of direct costs) – million Euros
Rep	47.758	The annual stack replacement costs (10% direct stack costs) – million Euros		**Rep**	15.4	The annual stack replacement costs (10% direct stack costs) – million Euros
LandWater	5	The cost of land lease and water supply – million Euros		**LandWater**	5	The cost of land lease and water supply – million Euros
CapEx (2020 cost level)	1777	The capital investment cost - million Euros		**CapEx (2020 cost level)**	830	The capital investment cost - million Euros
gridFee	24	The annual grid fees - million Euros		**gridFee**	24	The annual grid fees - million Euros
Number of cells in a stack	33	#		**Number of cells in a stack**	340	#
Number of stacks	1485	#		**Number of stacks**	96	#
stack per block	33	#		**stack per block**	8	#
block capacity	22	MW/block		**block capacity**	82	MW/block
Number of blocks	45	#		**Number of blocks**	12	#
rampRate	600	The rate at which block can vary - percent per hour		**rampRate**	600	The rate at which block can vary - percent per hour
Compressors per block	-	#		**Compressors per block**	-	#
Compressor min load	-	%		**Compressor min load**	-	%
Balance of Plant (BoP) min load	0	%		**Balance of Plant (BoP) min load**	0	%
BatteryCapex	207	capital investment for the battery system – million Euros		**BatteryCapex**	207	capital investment for the battery system – million Euros
Charge/Discharge rate	4	Hours (i.e., 25% capacity per hour)		**Charge/Discharge rate**	4	Hours (i.e., 25% capacity per hour)
Battery Energy Storage efficiency	90	%		**Battery Energy Storage efficiency**	90	%
Transformer-Rectifier losses	3.7-5.2	%		**Transformer-Rectifier losses**	3.7-5.2	%

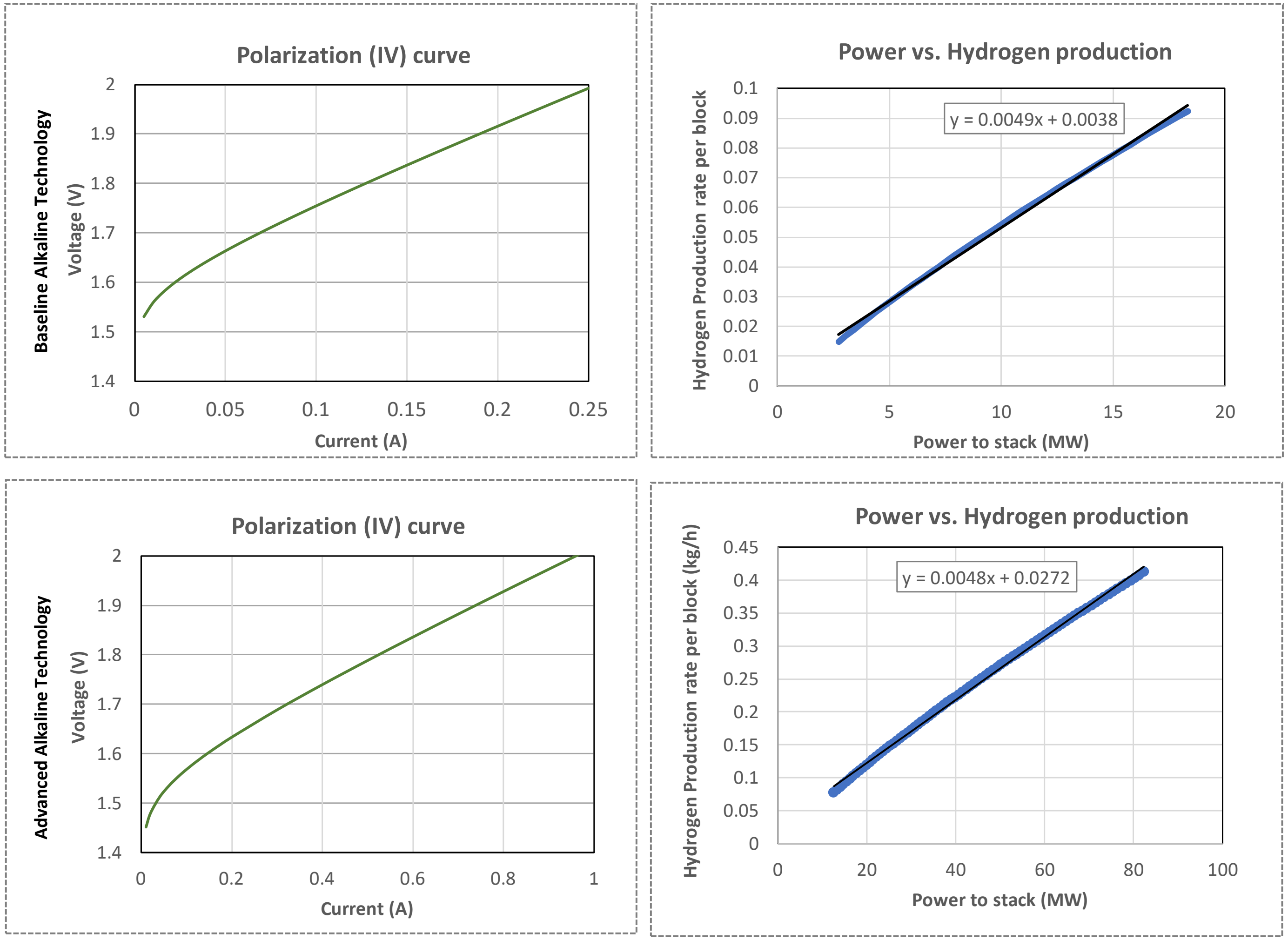


Fig. 2. The polarization curve (left), and Hydrogen Production Rate as a function of Power to Stack (right), for baseline (top) and advanced (bottom) Alkaline Technologies ([117], [118])

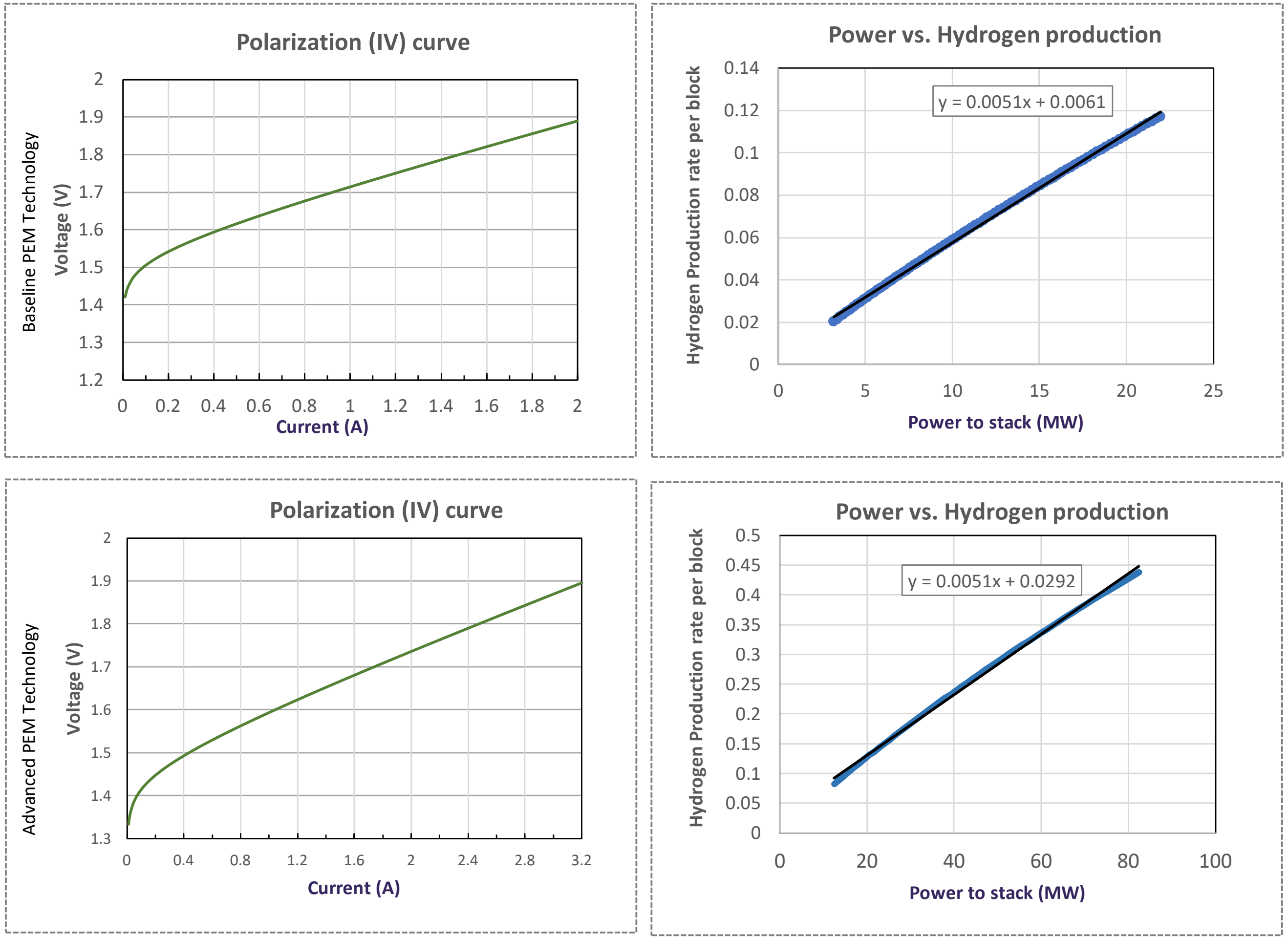


Fig. 3. The polarization curve (left), and Hydrogen Production Rate as a function of Power to Stack (right), for baseline (top), and advanced (bottom) PEM Technologies ([9], [10], and [11])

5. Results and discussions

This section presents and discusses the results, corresponding to Problems 1 to 4. **Table 3** reports the results of Problems 1-4. The main features of interest include the sensitivity of the levelized cost of hydrogen with respect to operational strategies (Subproblems 1-1,1-2, and 1-3), as well as process integration with batteries, overloading the stacks (i.e., under-designing them), and the arbitrage of the temporal electricity price differentials, as discussed in the following. The details of these results are presented in the online **Supplementary Materials**, and corresponding tables are listed in the first column of **Table 3**.

Problem 1: Shut-down strategies for near-minimum load operations

As discussed earlier, in **Problem 1** and its **subproblems** 1.1-1.3, the implication of various shut-down strategies for near-minimum load operations were investigated. The three top figures in **Fig. 4**. report the number of operating blocks for the three operational strategies formulated in **Subproblems 1.1**, **1.2**, and **1.3** (from left to right). The three bottom figures report the utilization of available wind power, for the three operational strategies, correspondingly.

A detailed comparison of various operational strategies for the four electrolyser technologies is presented in Tables **S1.1**, **S1.2**, **S1.3**, and **S1.4,** in the supplementary material. The results suggest that the first strategy in which all the electrolyser blocks operate at the same level and the electricity load is distributed evenly, offers average LCOH performance relative to the other shut down strategies. Therefore, the results of the first subproblem will be used as a reference for estimating the relative performance of the other two subproblems. The reason for this middling performance can be attributed to the lowest degree of freedom, and lack of flexibility. Further, it loses out on the opportunity to use any electricity generated below the minimum operating condition, meaning less hydrogen produced.

The performance of the third scenario in which the electrolyser blocks are shut off as soon as possible, leaving the minimum number of stacks utilized for a given power, is even worse. The reason should be attributed to the fact that the remaining stacks are operated at higher than necessary loads, and the efficiency of the stacks decreases when the load increases. While this may have impacts on degradation and aging of the membranes, good models for these do not exist, and so cannot be considered in the optimization.

The second scenario, however, offers the lowest LCOH. The improvements over the first operational strategy vary between 2.51% to 3.75%, and 0.153% to 9.23% of the LCOHs for Alkaline and PEM technologies, respectively. In this scenario, the electrolyser blocks are allowed to shut off as soon as the load is below a critical threshold. Above this threshold, the load of each electrolyser block is decided independently, with the aim of maximizing the energy conversion efficiency (i.e., producing more hydrogen) and minimizing the LCOH. The success of the second operational strategy should be attributed to the fact that it establishes a trade-off with maintaining the minimum number of stacks below the critical load while allowing more operational flexibility. As can be seen in the results, the lower critical loads result in better LCOH.

A graphical comparison between the three operational strategies is presented in **Fig. 4**. As can be seen in this figure (**Fig. 4.a.**), the stack blocks are either on or off, in the first operational strategy. Similarly, **Fig. 4.d.** shows that in the first operational strategy no effort is made to exploit the wind power after a critical level. By comparison, in the third operational strategy (**Fig. 4.c.**) only the minimum number of stacks are operational, and the stack blocks are shut down as soon as possible. The second operational strategy (**Fig. 4.b.**) has made a compromise by allowing stack shutdown only after a certain critical load. A striking observation is that the second and third operational strategy has very similar utilization of available wind power (**Figs. 4.e.** and **Fig. 4.f.**), despite the fact that they used a very different number of stack blocks. This observation suggests that there is no single optimal configuration for stack operation; instead, both the quantity and operational load of each stack must be finely tuned to achieve the lowest levelized cost of hydrogen (LCOH).

Problem 2: The economic implication of overloading the electrolyser blocks

In Problem 2, we investigated the economic implication of overloading the electrolyser stacks. Overloading the stacks for the same nominal operational load allows for reducing the required number of electrolyser blocks, and hence reducing the required capital investment. However, it also poses the risk of accelerated aging and degradation. These scenarios are also combined with the parametric exploration of the minimum load, in order to quantify the best economic performance. **Tables S2.1.**, **S2.2**, **S2.3.**, and **S2.4**. suggest that overloading stacks result in about 2.08%-6.27% and 3.75%-4.58% improvements for the Alkaline and PEM technologies, respectively. It is worth noting that these improvements in LCOH are generally less than the 10% decrease in capital cost might suggest. This is because the operation cost did not decrease, as the total amount of energy consumed was the same. Further, higher loading levels are also less efficient, so using stacks in overload conditions is less operationally efficient than standard conditions. These effects offset the improvement in the capital cost.

While the economic model suggests there is a benefit to reducing the total number of stacks and overloading them during high production periods, it is unclear how accelerated degradation and aging would impact the system. As we previously mentioned, there do not exist good models for the impact of operational level on degradation or aging, particularly with respect to overloading, so the replacement costs in the model were not changed. This means the LCOH results for this problem are artificially low. However, once better models or even estimates for degradation and aging have been developed, these results suggest that this proposal may be worth re-investigating to understand the potential improvements once degradation and aging have been accounted for.

Problem 3: Integrating with Battery Energy Storage systems

In Problem 3, integration with Battery Energy Storage (BES) systems was considered. The results are reported in **Tables S3.1.**, **S3.2**., **S3.3.**, and **S3.4**. The work initially examined a BES system of size equivalent to 25% of the electrolyser system, which can be found in the second row of these tables. However, only the same availability profile for wind electricity was considered. Generally speaking, the results counterintuitively suggest that integrating the BES system deteriorates the LCOH. This means that the capital cost of purchasing and installing the battery system is greater than the benefit gained in increased production. The BES allows for a more constant level of energy availability, but in this case the BES cannot hold enough energy to have a positive impact. Further, since the total energy availability is still the same, there isn’t ‘excess’ energy which can be harvested, meaning that any energy stored is energy which is being taken away from the electrolysers at the point in time it was stored. The only condition which benefits from BES is the baseline Alkaline condition, which benefits because the electrolysers are occasionally too slow to respond to changes in electricity supply. When the electrolysers are too slow, the BES allows the system to store the excess energy for use later.

The other scenarios in the abovementioned tables consider the additional provision of excess wind electricity of a range between 25% and 100% more than the original profile, along with varying BES system sizes. All results for these conditions have a lower LCOH than the reference condition, regardless of the size of the BES system, or the amount of excess energy. The results suggest a significant enhancement in the range of 9.13% to 22.97%, and 8.85% to 14.14% can be achieved, for the Alkaline and PEM technologies. The principal economic advantage of BES integration is derived from the utilization of surplus electricity, particularly in scenarios where the system is deemed 'undersized'. The alkaline systems again benefit the most from the use of the BES because they are slower to respond to changes in electricity supply than the PEM systems, and the BES gives an opportunity to store the extra energy that would otherwise be lost.

Problem 4: The economic implication of the volatility in the electricity price

Tables **S4.1**, **S4.2**, **S4.3**, and **S4.4** report the impact of the volatility in the electricity price on the levelized cost of hydrogen, when the system has a BES system and price volatility varies between 30-70%. The results suggest the LCOH can be reduced up to +2.34% when the volatility is as high as 70%. Generally speaking, increasing the volatility of the electricity price decreases the LCOH, as there is greater opportunity for arbitrage. Also, the advanced versions of both technologies had a greater decrease in their LCOH due to arbitrage than the baseline versions. Due to higher conversion efficiencies, the advanced versions of both technologies benefit more from constant power supply than do the baseline versions, thus improving the performance. Further, both technologies benefited a similar amount of the volatility, without there being a large difference in the LCOH results between technologies for each volatility level.

Additional insight can be gained from the visual presentation in **Fig. 5**. For the sake of clarity, a sample segment of the operational time horizon is shown. From this figure, it can be seen that when the availability of wind power is low (time window shown by ΔT_1), all the available power is consumed by the electrolyzers. In such circumstances, the stored electricity is also consumed by the electrolysers. Under these conditions, the economic loss associated with unutilized stacks is higher, and electricity is purchased at any costs. By comparison, when the availability of wind power is high, there is an option to utilize the stored electricity (as in ΔT_4) or purchasing additional wind power for storage (as in ΔT_2 and ΔT_3), depending on the price of the electricity.

Table 3. The summary of the sensitivity analyses for various technologies, with respect to the minimum load operational strategy, overload operation, battery integration, and volatility in the electricity price. Details of these sensitivity analyses are presented in Supplementary Materials, and corresponding tables are presented in the first column. The variations in the 5th column are with respect to Problem 1 of the same technology. The sign "+" refers to a reduction in LCOH.

Table # SM	Technology	Sensitivity Variable	Outperforming Scenario/Conclusion	Variation in LCOH	Best LCOH (Euros/kg H_2)
S1.1.	Baseline Alkaline	Minimum load operation	2nd operational strategy (Subproblem 1.2)	-2.11% to +3.75%	5.88
S1.2.	Advanced Alkaline	Minimum load operation	2nd operational strategy (Subproblem 1.2)	-6.26% to 3.34%	4.24
S1.3.	Baseline PEM	Minimum load operation	2nd operational strategy (Subproblem 1.2)	-5.938% to 2.948%	6.03
S1.4.	Advanced PEM	Minimum load operation	2nd operational strategy (Subproblem 1.2)	-7.47% to 9.23%	3.90
S2.1.	Baseline Alkaline	Overload	Economic gains at the risk of accelerated aging	Up to +6.42%	5.49
S2.2.	Advanced Alkaline	Overload	Economic gains at the risk of accelerated aging	Up to +10.98%	3.76
S2.3.	Baseline PEM	Overload	Economic gains at the risk of accelerated aging	Up to 6.81%	5.65
S2.4.	Advanced PEM	Overload	Economic gains at the risk of accelerated aging	Up to 12.92%	3.76
S3.1.	Baseline Alkaline	Battery integration	100% battery capacity /200% more availability of electricity	4.63% to +22.97%	4.48
S3.2.	Advanced Alkaline	Battery integration	100% battery capacity /200% more availability of electricity	-1.67% to +9.13%	3.84
S3.3.	Baseline PEM	Battery integration	100% battery capacity /200% more availability of electricity	-2.43% to 14.14%	5.17
S3.4.	Advanced PEM	Battery integration	100% battery capacity /200% more availability of electricity	-1.56% to 8.85%	3.54
S4.1.	Baseline Alkaline	Volatility in the electricity price (30%-70%)	Higher volatility results in more gains, when integrated with a battery	Up to +0.42%	4.46
S4.2.	Advanced Alkaline	Volatility in the electricity price (30%-70%)	Higher volatility results in more gains, when integrated with a battery	Up to +2.34%	3.75
S4.3.	Baseline PEM	Volatility in the electricity price (30%-70%)	Higher volatility results in more gains, when integrated with a battery	Up to 1.74%	5.08
S4.4.	Advanced PEM	Volatility in the electricity price (30%-70%)	Higher volatility results in more gains, when integrated with a battery	Up to 2.26%	3.46

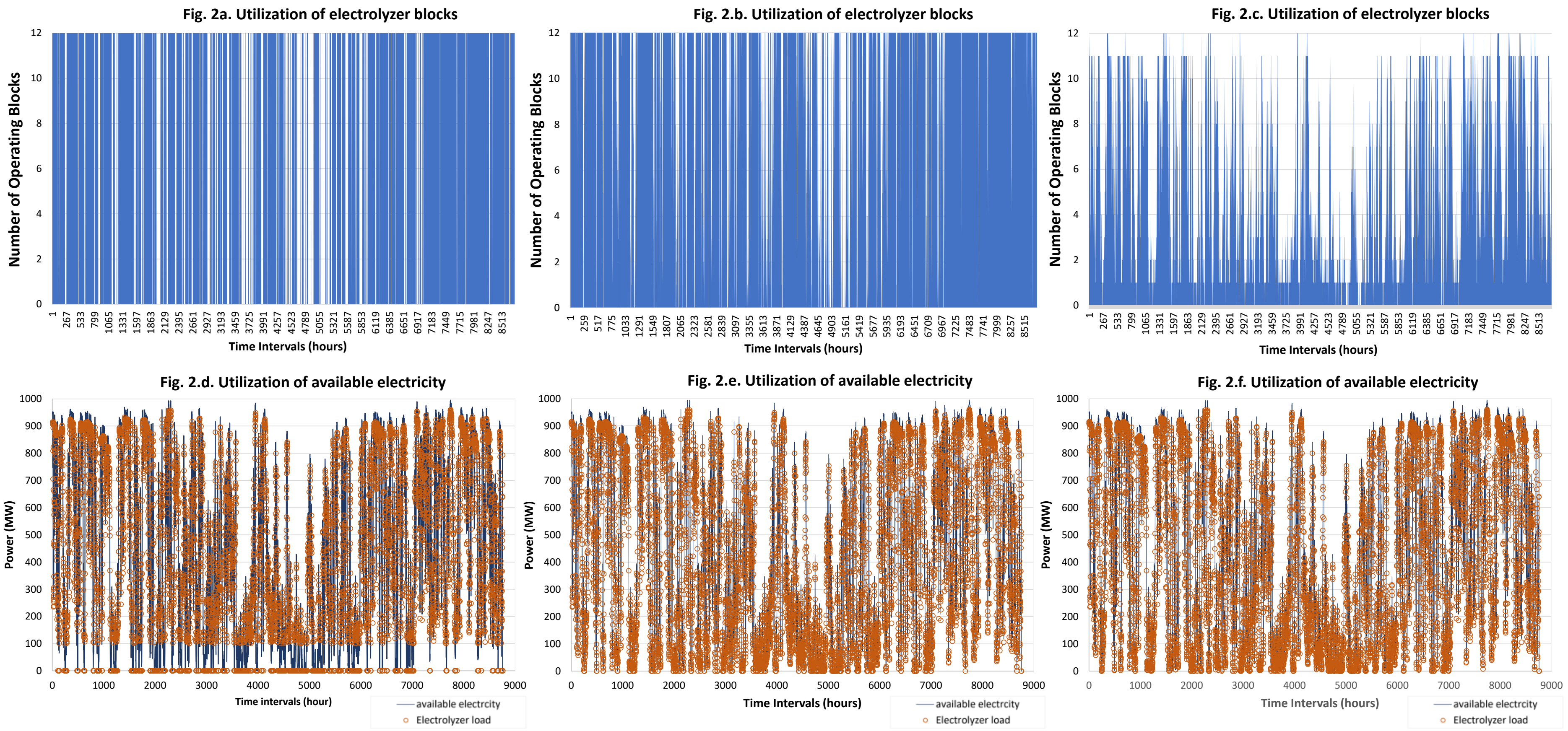


Fig. 4. The number of operating blocks and the utilization of available wind power, for the three operational strategies corresponding to Subproblems 1.1, 1.2, and 1.3 (from left to right). The results are presented for the advanced PEM technology, with 2% minimum load.

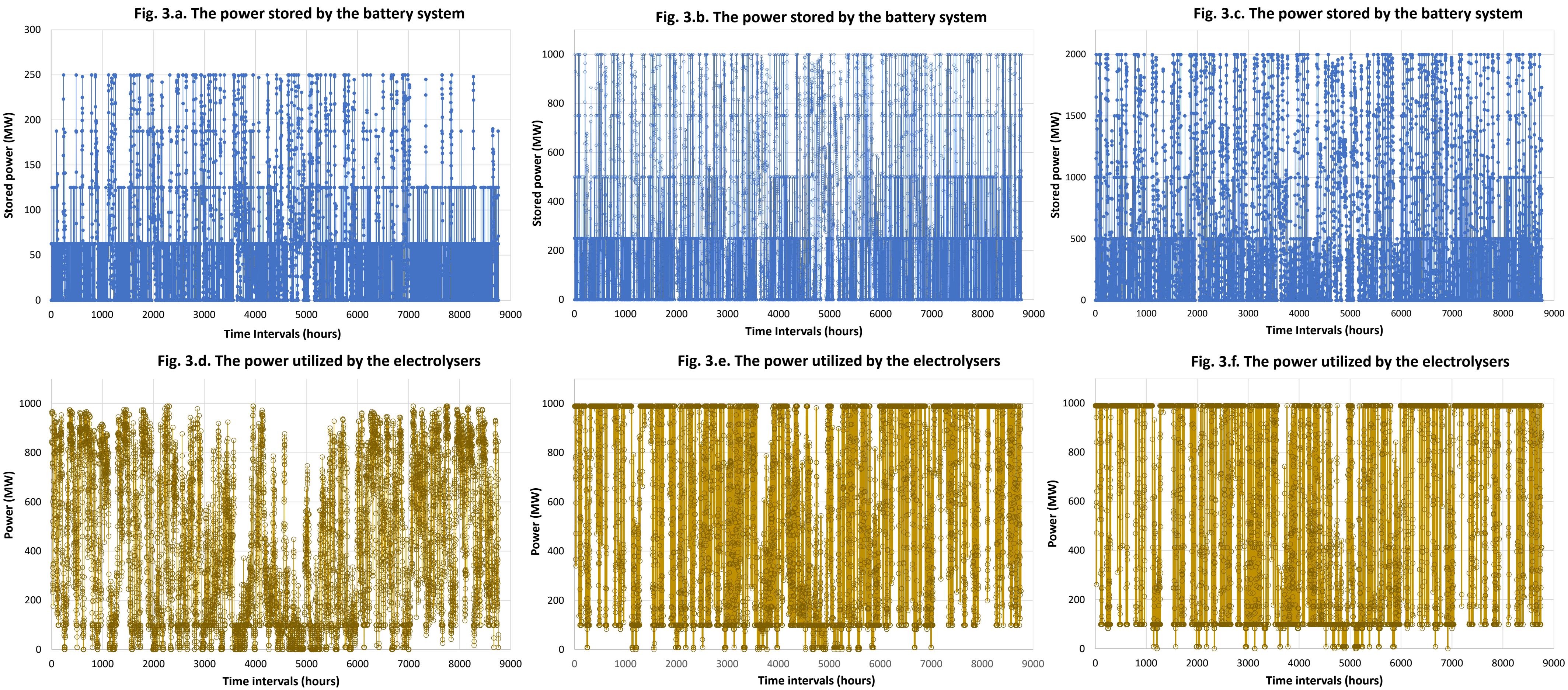


Fig. 5. The power stored at battery energy storage (BES) systems with different capacities (250, 1000, 2000 MWh, from left to right top figures), and corresponding power utilizations by the electrolysers (bottom figures). The results are presented for the advanced PEM technology, with 2% minimum load.

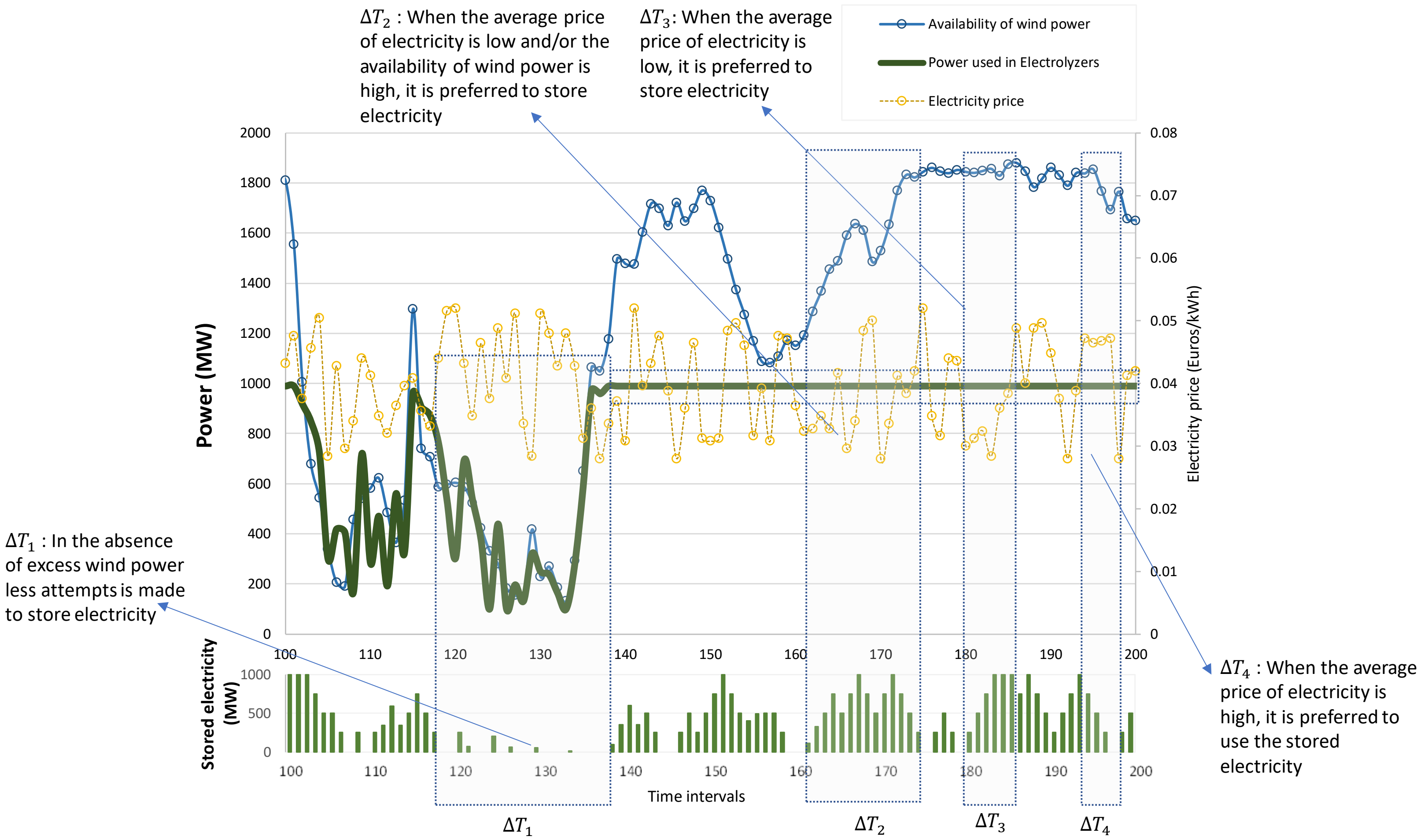


Fig. 6. The performance of an advanced PEM system integrated with a battery energy storage of the same size, under the second operational strategy, and 30% volatility in the electricity price. The available wind power, power used by the electrolysers, electricity price, and stored electricity are displayed to illustrate trade-offs in the system.

Conclusion and future research

Realizing the green hydrogen potentials for harnessing and storage of renewable energy strongly depends on the flexible and economic operation of electrolyser technologies. The present research quantitatively explored flexible operational strategies of various electrolyser technologies through minimum load and partial shutdown transitions as well as overload operations, battery integration, and operating under variable energy tariffs.

Several key conclusions can be drawn upon careful observation of the results:

- For the shutdown strategies near minimum load (Problem 1), independently optimizing the load of each electrolyser block while restricting shutdowns until after a critical system load offered the lowest LCOH. This approach reduced costs by 1.53-9.23% compared to even load distribution or minimizing operating stacks. The gains resulted from enhanced operational flexibility while maintaining high average stack loading.
- Allowing short-term overloading of electrolyser stacks by 10% (Problem 2) lowered LCOH by up to 6.81% for alkaline and 4.58% for PEM systems. These benefits stemmed from reducing installed capital costs by undersizing the stacks, although accelerated aging from sustained overloading was not considered. Technological improvements that increase the safe overload capacity and duration could unlock further significant economic potential.
- Battery energy storage integration (Problem 3) significantly cut LCOH by 4.63-22.97% for alkaline and 1.56-14.14% for PEM when excess renewable electricity was available. With 25% extra generation, a 100% battery capacity achieved the maximum cost reduction. The storage increased asset utilization and exploitation of cheap electricity.
- Higher volatility in electricity prices (Problem 4) produced greater arbitrage potential, lowering LCOH up to 2.34%. Advanced electrolysers benefited more from stable input power enabled by the storage.

Alkaline electrolysers demonstrated greater economic advantage when integrated with battery systems, particularly in response to the variability of wind power supply, benefiting more from this integration compared to PEM electrolysers (Table3). It was also noted that enhancing the dynamics of electrolysers and as well as battery energy storage systems will have great potential for economic and flexible integration of these systems with renewable energy, which should be the focus of future research.

The results suggest that battery integration has the highest impact on improving LCOH, followed by overload operation, and flexible near load operation. These observations suggest a potent research pathway for exploring and mitigating uncertainties associated with these technologies.

Startup time of electrolysers from the off state was not considered in this work. Incorporating startup time delays upon restarting alkaline stacks would enhance the model accuracy for assessing flexible operation. Evaluating the model under more diverse wind and climate conditions merits future work to understand geographical variations. Analysis of temporal fluctuations in renewable generation profiles would also be valuable.

Expanding the analysis to encompass other renewable power sources like solar photovoltaics could offer useful comparisons on the value of flexible operation strategies. Hybrid systems with both wind and solar generation may achieve more consistent output than individual resources.

This work considered a standalone wind-hydrogen system. Connecting the electrolysers to the grid could enable more stable input power and electrolyser loading at the cost of higher electricity prices. Comparative studies on grid-connected versus isolated systems present another area for further investigation.

Overloading was modelled without accounting for impacts on stack degradation and replacement costs. Incorporating degradation effects is critical to fully weigh the trade-offs between improved asset utilization and accelerated component aging from overloading.

While the current model utilized an hourly time resolution, evaluating sub-hourly fluctuations in generation and loading could reveal additional challenges and strategies for highly dynamic operation.

Uncertainty analysis through Monte Carlo simulation would allow assessing the robustness of control strategies across probable variability in key technical and economic parameters. Optimization under uncertainty represents a logical extension to this deterministic approach.

Overall, the present model provides a flexible framework for evaluating novel operational regimes to balance efficiency, flexibility, and cost. The findings indicate significant potential to optimize renewable hydrogen systems through advanced operational strategies and integration. Building on this foundation, future work should explore diverse conditions, renewables, temporal patterns, grid interactions, degradation modelling, and uncertainty to further advance flexible and economical renewable electrolysis systems. With expanded scope and enhanced models, the optimization approach demonstrated here can continue generating critical insights guiding development of robust policies, designs, and control strategies for sustainable hydrogen production.

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Nomenclature

Sets

i	Block numbers
k	Electrolyser technologies [AWE Baseline, AWE Advances, PEM Baseline, PEM Advanced]
t	Time periods
e	Electricity tiers [wind, ppa]

Scalars

ε	Tolerance level for the optimisation
CCF	Capital charge factor
n	Lifetime of plant in years (years)
r	Discount rate
$CapConv$	Capital investment converter (Mill. €)
Δt	Length of time step in hours (hours)
Δt_s	Length of time steps in s (s)
Eff_{conv}	Converter efficiency
$minLoad$	Minimal load of blocks (fraction)
$sysCap$	Overall system capacity (MW)
$BattEff$	Energy conversion efficiency during charging and discharging the battery system

$BattSysCap$	The capacity of the battery energy storage system
$CaptlExpnc$	Capital cost of the battery energy storage system
$BatteryCaptlExpnc$	Operating costs of the battery energy storage system
$MaxChargeRate$	The maximum rate of charging the battery energy storage system
$MaxDischargeRate$	The maximum rate of discharging the battery energy storage system
$gridFee$	Annual grid fees (Mill €)
$OpMain$	Annual operations maintenance costs, 2% of direct costs
$OpMainBatt$	Annual operations maintenance costs of the battery energy storage system, 2% of direct costs
Rep	Annual stack replacement costs, 10% direct stack costs
$LandWater$	Cost of land lease and water supply

Tables

$blockCost(k)$	Investment cost for stack types for each stack technology, and number of stacks, & includes block level balance of plant (Mill. €)
$Elec_{price}(t,e)$	Electricity price at any time in any price tier (k€ MWh-1)
$SHP_{fix}(k)$	Specific hydrogen production offset for each stack technology, and number of stacks (kg s^{-1})
$SHP_{var}(k)$	Specific hydrogen production for each stack technology, and number of stacks (kg s-1 per MW)
$blockCap(k)$	Block power capacity for each stack technology, and number of stacks (MW)
$sBoPElec_{fix}$	specific BoP electricity consumption offset / axis intercept for each stack technology, and number of stacks (MW)
$sBoPElec_{var}$	specific BoP electricity consumption for each stack technology, and number of stacks (MW per MW stack)
$RampDown_{max}(i,k)$	Maximum ramp rate down as a fraction for each stack technology, and number of stacks (% hr^{-1})
$RampUp_{max}\ (i,k)$	Maximum ramp rate up as a fraction for each stack technology, and number of stacks (% hr^{-1})
$Elec_{avail}(t,e)$	Available electricity at any time in any price tier (MW)

Variables

$LCOH$	Levelised Cost of Hydrogen (€ kg^{-1})
D	Iteratively varied scalar used to optimise the system
$O(i,k,t)$	Binary variable for the activity (on/off) of a specific block number, technology, and number of stacks combination
$Q_{hydrogen}$	Total amount of hydrogen produced in a year (Mill. kg)
$Hydrogen(i,k,t)$	Hydrogen production rate in any time period of a specific block number, technology, and number of stacks (kg s^{-1})
$Hydrogen_{sys}(t)$	Total hydrogen production in any given time period (kg)
$Elec_{use}(t)$	Electricity consumption in any given time period (MW)
$ECE(t,e)$	Electricity consumed in tier e in any given time period (MW)
$Power_{block}(i,k,t)$	Power loading level for a specific block, technology, and number of stacks in any given time (MW)
$power_{BalanceOfPlant}(i,k,t)$	Power consumption of the balance of plant for a specific block number, technology, and number of stacks at any given time (MW)
$numBlocks(i)$	Cardinality of the set of block numbers (j) referring to the number of its elements
$CaptlExpnc$	Capital expense of the system annualized over time (Mill. €)
$OpntExpnc(t)$	Operating expenses of each time period (k €)

$TotalCost$	Total cost to operate per year (Mill. €)
$rampRateDown(t)$	Rate at which electrolysers can ramp down (MW)
$rampRateUp$	Rate at which electrolysers can ramp up (MW)
$PowerRamp_{Down}(i,k)$	Rate at which electrolysers can ramp down (MW)
$PowerRamp_{up}(i,k)$	Rate at which electrolysers can ramp up (MW)
$sBoPElec_{fix}(i,t)$	Specific balance of plant power usage (MW)
$sBoPElec_{var}(i,t)$	Specific balance of plant power usage (MW)
$EnergyStorageChange(t)$	Changes in the energy stored in the battery energy storage system
$PowerStorageChange(t)$	Changes in the power stored in the battery energy storage system
$StoredEnergy(t)$	The amount of energy stored in the battery energy storage system within a time interval