Carbon Emission Reduction Mechanisms in Hydrogen - Electricity Coupling Systems Leveraging Renewable Energy: A Power Quality - Centric Analysis

Ye Bin[1], Xu Bin[1], Wang PingPing[1], Liu Zhimin[1], Zhang Yufeng[2,*]

[1]State Grid Anhui Electric Power Co., Ltd. Anhui Hefei, 230009
[2]State Grid Ying Da Carbon Asset Management (Shanghai) LTD. Shanghai, 200126

Abstract

Decarbonizing power generation is accomplished through coupling renewable energy with long term energy storage, primarily through the use of a hydrogen electricity coupling system. This paper considers the effectiveness in mitigation of carbon emissions, power quality enhancement and balancing supply demand variability of such systems. Smoothing of energy availability over time is achieved when we store hydrogen, and the initial carbon emissions decrease when we install it. Power quality metrics such as voltage stability, harmonic distortion, and reactive power management are acceptable in the system and the system is technically viable. The findings reveal a potential of mid-century carbon neutral goals are revealed by hydrogen as a reliable energy vector. Basically, the study gives a hydrogen-electricity coupling model that integrates wind, solar, biomass, and other renewable energy sources, hydrogen production, storage, and grid power delivery as one operational structure. The simulations conducted on MATLAB/Simulink showed with good quality and fast response that the system possessed stable power quality and performed energy conversion efficiently with whatever the variable renewable input conditions were.

*Corresponding Author: Email: zhangyf188688@163.com, zyufeng88@outlook.com

1. Introduction

Reducing greenhouse gas emissions has emerged as a universal goal due to the worsening climate change crisis; therefore, the shift to a low-carbon energy system has become inevitable. Hydrogen-electricity synergy, which combines hydrogen generation and storage with power generation, has become a potential way to contribute to decarbonization and promote the improvement of the flexibility of the energy system [1-2]. Solar and wind power systems, while being environmentally friendly, are some of the most intermittent energy sources that can be named. These cause a mismatch in energy supply and demand resulting in moderation of challenges in grid stability and the integration of renewable energy. Although there is a growing curiosity for power systems based on hydrogen, there are still major obstacles to be overcome, mainly concerning the instability of voltage and harmonic

distortion. These problems become more pronounced with the use of renewables such as wind and solar, which are intermittent in nature and cause the power quality to fluctuate. It is important to resolve these issues to guarantee the stability and trustworthiness of hydrogen-based systems in the actual scenario of their usage.

To avoid these problems, hydrogen can be generated through the process of electrolysis in which it can be produced when there is excess renewable electricity and then used in the fuel cells to generate the electricity in situations where generation is low or peak hours [3] As opposed to conventional battery storage, which is limited in terms of duration and scalability, hydrogen has the advantage of long duration, high capacity storage that can resolve seasonal imbalances in energy [4]. The coupling of hydrogen and electricity provides advantages in long-duration storage over batteries and pumped hydro by having more energy retention, being able to store large amounts of energy, and being more efficient in seasonal storage situations. In addition to increasing the dispatchability of renewable energy, this ability also helps energy security by separating energy production from energy consumption in time and space.

In a form powered by renewable sources, electrolysis hydrogen production does not lead to direct CO_2 emissions, making its use a key pathway to carbon neutrality in the power system [5]. The hydrogen-electricity coupling framework that has been proposed complies with the Energy Web paradigm, as it allows ICT-based supervision and control of distributed energy resources. By the data-supported management of renewable generation, hydrogen storage, and power delivery, the system facilitates smart energy flow optimization, lower carbon intensity, and integration within future techno-social energy ecosystems that are larger in scale and more widespread.

Nevertheless, hydrogen electricity systems have their technical and economic drawbacks. There are many issues, but power quality is certainly one of the top concerns. Under weak or isolated network conditions, electrolyzers and fuel cells introduce voltage fluctuations, transient events, as well as harmonic distortions into the grid [6]. The sources of these disturbances are the dynamic and nonlinear nature of hydrogen energy conversion systems that operate under rapidly changing load profiles and switching frequencies [7]. If not managed appropriately, voltage transients and frequency deviations can cause any sensitive grid-connected equipment to become unstable and affect its performance [8].

One of the biggest problems for power quality is harmonic distortion, particularly. The use of hydrogen systems with the power electronic converters generates high-frequency harmonics that can lower the efficiency of the system, overheat the components and perturb industrial operations [9]. These effects demand strong filtering strategies, such as active and passive filters in the presence of robust filtering, such that the IEEE 519 standards for total harmonic distortion (THD) [10], [11] are satisfied. Furthermore, both control algorithm design and converter

topology must be optimized to the point that it enables stable integration to modern smart grids [12–14].

Beall's List proposes a new decentralized approach for management of human resources data. The approach is ruled by the "three" technologies: blockchain, AI, and predictive control promising data security, scalability, and efficiency that are far better than those available through centralized systems, thus overcoming their challenges. The proposed method, which is somehow inspired by this integration, does exactly that - applies to HR data management similar technologies to strengthen security, making decisions faster and paving the way for more people to access the data since it is decentralized and thus optimized [15].

As hydrogen technologies are deployed much more widely within renewable energy frameworks, they have to be assessed with regard to their real-world impact on carbon emissions and power quality. This study aims to explore the mechanisms for carbon emission reduction enabled by hydrogen – electricity coupling and evaluate their impacts on power quality in renewable integrated grids.

The remainder of the study is organized as follows: Section II reviews related works the hydrogen–electricity coupling and the renewable energy. Section III details the proposed system, including the architecture, the modeling method and the power quality methods. Results and discussion of the simulation outcomes, as well as CO_2 reduction and comparison with conventional systems are presented in section IV. In the last section V we conclude with the recommendations of the optimization, system reliability and future research.

2. Related Works

2.1 Overview of Hydrogen-Electricity Coupling

Hydrogen-electricity coupling is a cost-effective means that addresses intermittency challenges such as renewable energy systems and help support long term decarbonization goals. Here, any excess electricity created from solar and wind resources is used to produce hydrogen through electrolysis. It is then stored, and when there is peak demand or when there is not enough renewable generation are can be reconverted to electricity using fuel cells. In addition, it increases energy security and grid flexibility, and helps to decrease CO_2 emissions and decrease dependence on fossil fuels [16]. There has been a noticeable trend in recent publications to perform quantitative performance comparisons of hydrogen-electricity coupling in hybrid renewable energy frameworks [17]. The studies indicate that there are not only measurable increases in grid stability but also better operational resilience during renewable variability [18]. The reports have it that the comparative efficiency evaluations have hydrogen coupling systems as the winners

over the traditional storage in long-duration applications, especially in the case of maintaining stable grid operation while allowing higher renewables penetration [19].
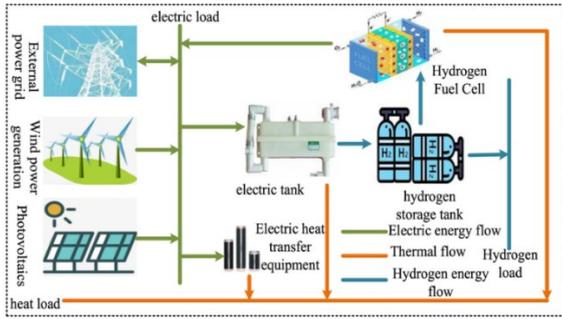

Figure 1. System architecture of hydrogen–electricity coupling integrating wind and solar energy for hydrogen production, storage, and reconversion via fuel cells [15]

A hydrogen-electricity coupling system integrating wind and solar power for production of the hydrogen to be stored in hydrogen tanks for future use in hydrogen fuel cells to produce electric loads and heat loads is also defined in Figure 1. It also indicates energy flow pathways such as electric, thermal, and hydrogen energy flows to enhance utilization of renewable resources.

2.1.1 Electrolysis for Hydrogen Production

Electrolysis is a widely used method for hydrogen production through the decomposition of water to generate hydrogen and oxygen. Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM) Electrolysis, and Solid Oxide Electrolysis (SOE) [20] Eliyä are used in the process and hence this process has varying efficiency, cost and performance. Alkaline electrolysis (AE) is a mature, large scale technology with a liquid alkaline electrolyte of KOH or NaOH. It is 80–160°C operated with a diaphragm between nickel, cobalt, or iron electrodes. Although it is cost effective and durable, integration with intermittent renewables is not possible due to its reliance on stable power [21].

PEM Electrolysis utilizes a solid polymer membrane allowing only H^+ ion passage, with iridium and platinum electrodes. Operating at 50–80°C, it offers high power density and rapid response, making it suitable for solar and wind use. However, its high cost and fuel sensitivity are notable drawbacks [22]. Solid Oxide electrolysis (SOE) functions at 600–1000°C using a ceramic electrolyte. Water reacts at the cathode with electrons to form hydrogen and oxygen ions, which migrate to the anode to release oxygen gas. SOE can exceed 80% efficiency with industrial waste heat, though material degradation and complex maintenance limit its renewable energy compatibility [23]. In contrast to PEM water electrolyzers, the solid oxide electrolysis devices subjected to frequent start-stop actions are under high thermal and material

stress, which may, over time, limit their use in renewable integration situations where long-term durability is needed, but on the other hand, PEM technology provides operational durability being more robust under variable power conditions.
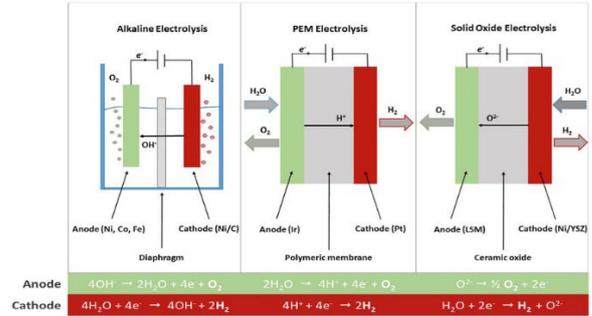

Figure 2. Comparison of Alkaline, PEM, and Solid Oxide Electrolysis, showing their working principles and reaction mechanisms [20]

Figure 2 presents a comparative analysis of Alkaline, PEM, and Solid Oxide Electrolysis technologies and discusses how such technologies can be paired with the proposed hydrogen-electricity coupling system integration in view of the difference in the electrode material used, ion transport mechanism, and the reaction efficiency.

2.1.2 Fuel Cells for Electricity Regeneration

Once hydrogen has been generated and stored, the electrolysis can feed the hydrogen to a fuel cell, where it can be reformed into electricity once again. In a controlled electrochemical reaction with oxygen, the electricity from hydrogen can be produced by fuel cells. PEMFCs and SOFCs are the two most developed fuel cell technologies for hydrogen electricity coupling systems. Figure 3 illustrates operating Regenerative Fuel Cell (RFC) system by generation of hydrogen (H_2) and oxygen (O_2) from electrolysis of water using electrical energy, and forms a closed loop process which is conducted to drive the system. The stored hydrogen is recombined with oxygen in the fuel cell to produce electricity during energy demand, when energy storage is efficient and energy is also used well.
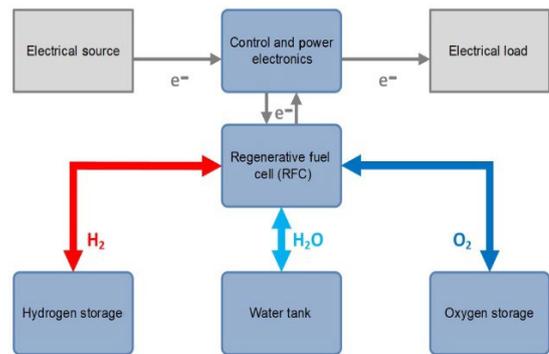

Figure 3. Regenerative fuel cells [21]

Fuel cells have the ability to ensure power stability and grid resilience but also provide harmonics and transient voltage variations to the power network. Electrical disturbances need to be filtered out and the real time control demands to meet grid standards must be satisfied using advanced power electronic interfaces.

2.2 Comparison with Alternative Storage Methods

To highlight the system's role in grid stability and long-term storage, Table 1 offers a comparative overview of hydrogen-based storage versus other technologies.

Table 1: Comparison of energy storage technologies (hydrogen, batteries, pumped hydro)

Storage Type	Efficiency	Duration	Cost/Scalability	CO_2 Emissions	Response Time
PEMFC + H_2	50–60%	Long (days)	High (modular design)	Near-zero	Moderate
Li-ion Battery	90–95%	Short (hrs)	Moderate (limited life)	Low (indirect)	Very fast
Pumped Hydro	70–85%	Long (days)	High (site-specific)	Near-zero	Slow

While batteries are efficient for short-term applications, hydrogen storage offers unmatched capacity for long-duration, seasonal, and large-scale backup making it highly relevant in the context of net-zero energy systems.

3. System Design and Analysis

3.1 Proposed System Architecture and Operation

A hydrogen electricity coupling system includes renewable energy sources for hydrogen production, storage, and electricity generation by combining solar photovoltaic (PV) cells and wind turbines to supply DC to the grid, or to generate hydrogen by electrolysis. Surplus renewable energy is converted to hydrogen gas (H_2), using electrolyzer, stored in high pressure tanks / cryogenic systems for later use. Carbon footprint reduction is tracked on the CO_2 Emission Monitoring System and life cycles of the system is assessed on the basis of Life Cycle Assessment (LCA). Stored hydrogen can be made into electricity through fuel cells for zero direct carbon emissions at times either when renewables are unavailable or at peak times. DC to AC conversion process is employed to provide voltage stability and harmonics control mechanisms before converting DC to AC for grid integration to maintain power quality and grid stability. Following the outlined structure, the STATCOM takes care of the reactive power required for voltage control while the APF simultaneously removes the harmonics. Together, they are the ones who are responsible for the stabilization of the grid, the reduction of THD, and the guarantee of an almost ideal power factor. Electric loads or the power grid can receive the final low carbon energy output for use or be supplied to the power grid for use, improving energy resilience and sustainability.
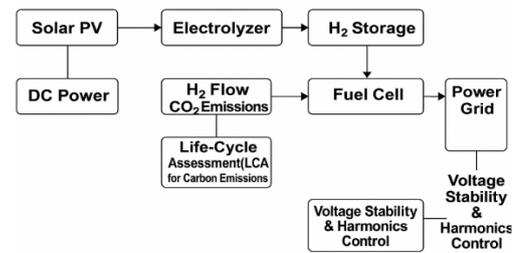

Figure 4. Proposed hydrogen-electricity coupling system architecture, illustrating energy flow from renewable sources (solar PV and wind) to electrolysis-based hydrogen production, storage, and conversion back to electricity via fuel cells for grid and load supply

A hydrogen electric system that couples the DC power from solar PV and wind turbines to produce hydrogen is shown in Figure 4. Hydrogen is produced, stored and then converted into electricity by a fuel cell that supplies the electric loads as well as the grid. The carbon footprint reduction is tracked by a CO_2 Emission Monitoring System and a Life Cycle Assessment (LCA) measures the system's total environmental impact such that it is a low carbon energy transition. The elements of the MATLAB/Simulink model including renewable energy sources, PEM electrolyzer, hydrogen storage, fuel cell, inverter, and CO_2 emission monitoring correspond directly. This mapping guarantees that the performance analysis being done by simulation is consistent with the conceptual system architecture.

3.2 System Design and Configuration

The renewable energy sources coupled to the hydrogen-electricity are solar photovoltaic (PV) panels and wind turbines which jointly produce DC power. It can be directly fed to the power grid or used for hydrogen production by an electrolyzer. The system is designed to make energy efficient, reduce storage losses and keep the grid integration at a stable level. The methodology is structured with respect to renewable energy integration, electrolysis process-based hydrogen production, hydrogen storage, emission of carbon measurement, power quality assessment and system performance validation.

The modeling framework actually considers all the previously discussed elements at the same time through the dynamic interactions among the feedback mechanisms of grid voltage and frequency, the patterns of renewable intermittency, and the characteristics of the electrolyzer load response, to accurately depict both transient and steady-state system behaviors. The integrated approach makes it possible to evaluate the system stability, speed of response, and power balance during the scenarios of changing renewable input and grid disturbance.

3.3 Renewable Energy Integration

The DC electricity is generated first from solar PV and wind turbines as primary energy sources. These sources are selected for their availability, cost effectiveness, and ability to function on their own without the dependence on fossil fuels. Polycrystalline cells are used in solar PV panels who has maximum power point tracking (MPPT) controller to optimize the power output. Wind turbines are designed to operate at variable speeds under the condition of pitch control for stable wind turbines generation. The DC power produced is efficiently controlled to optimally balance the direct grid supply and hydrogen production. The efficiency of renewable energy conversion has a significant impact on the overall system sustainability because higher efficiency implies increasing production of hydrogen with effectively little loss of energy [24]. A Mixed-Integer Linear Programming (MILP) based optimization framework is proposed as a means of advancing system sustainability even further. The planned framework is to perform the optimization of dispatch scheduling, load balancing, and the management of hydrogen storage, hence ensuring the energy loss is kept at the lowest level, the operational costs are reduced, and the grid integration efficiency is improved through the smart energy flow management.

3.4 Hydrogen Production through Electrolysis

This system employs a proton exchange membrane (PEM) electrolyzer, selected due to its high efficiency, rapid response to renewable energy fluctuations, as well as lower operational temperature than do alkaline electrolyzers. The process of electrolysis involve a splitting

of water (H_2O) into hydrogen (H_2) and oxygen (O_2) by the use of electrical energy. Under steady state conditions PEM electrolyzer works in a voltage range 1.8–2.2 V per cell with efficiency from 65% to 80%. This generated hydrogen is stored for further use in electricity generation [25]. The PEM electrolyzer not only has a very high efficiency, but also shows fast dynamic response characteristics, which means it can adjust quickly to the changes in renewable energy input. The fast response permits the effective following of the changing solar and wind power, and this results in a reduction of energy curtailment and stable hydrogen production under eco-friendly but intermittent operating conditions, which is an additional advantage of the process.

The model's reliability was tested by comparing the simulated results with the laboratory measurements, which had chosen the PEM electrolyzer operating voltage range (1.8–2.2 V) and efficiency (65%-80%) as the criteria. This not only ensures that the model's voltage–efficiency characteristics are in line with the real performance but also guarantees that the working conditions are accurately represented and thus the trustworthiness of the system is reinforced as shown in Table 2.

Table 2. PEM electrolyzer operating parameters

Parameter	Value
Voltage	1.8-2.2 V per cell
Efficiency	65%-80%
Temperature	60ºC-80ºC

The electrolyzer operational dynamics are carefully monitored so as to minimize losses in power and reach highest possible hydrogen conversion efficiency. The PEM electrolyzer model is significantly advanced by the inclusion of electrochemical kinetics parameters such as exchange current density, activation overpotential, and proton conductivity. Considering these parameters, the accuracy of the electrolyzer model is enhanced to the level of actual electrochemical conversion efficiency and the system's performance during the use of variable renewable energy inputs is also improved.

The efficiency of the electrolyzer is calculated by using the following formula:

$$\eta_{Electrolyzer} = \left(\frac{E_{hydrogen\,output}}{E_{electrical\,input}} \right) \times 100 \qquad (1)$$

Where:

$E_{hydrogen\,output}$ is the energy stored in hydrogen (kWh)

$E_{electrical\,input}$ is the electricity consumed during electrolysis (kWh)

This equation measures the percentage of input electrical energy converted into chemical energy in hydrogen. A higher efficiency indicates better energy utilization by the electrolyzer. Values are calculated based on current-voltage profiles during steady-state simulation..

3.5 Hydrogen Storage and Management

Once produced, hydrogen can be stored in the form of high pressure tanks or cryogenic storage for subsequent use to generate power in fuel cell power generation. Energy density, cost efficiency and grid demand have an influence on the decision of storage method. Hydrogen storage at 350–700 bar provides an energy capacity storage balance with good storage safety. Cryogenic storage stores hydrogen at -253°C, which results in higher energy density and more stable long term storage. Different methods will be chosen based on power grid demand cycles, system integration requirements and power cost benefit analysis.

Hydrogen storage efficiency requirements are critical to achieve maximum energy utilization. Methods of minimizing storage losses are employed that include advanced insulation techniques and thermal management systems. This is also achieved in terms of real time monitoring of the hydrogen levels, pressure, and temperature to optimize storage performance. The proper storage-to-grid dispatch planning can reduce the unnecessary hydrogen losses and maximize the overall system efficiency [26].

3.6 Carbon Emission Monitoring and Life Cycle Assessment (LCA)

To track the reduction of carbon footprint, a CO_2 Emission Monitoring System is integrated into the framework. It evaluates the environmental impacts of the hydrogen electricity coupling process using emissions from a renewable hydrogen power generation compared to traditional fossil fuel based power generation. Therefore, the methodology is compared based on real-time CO2 emissions from the system with that of conventional power generation. The CO_2 Emission Monitoring System periodically cross-validates emission data at the defined simulation time intervals, thus, guaranteeing that the carbon output measurement is uninterrupted and trustworthy all through the system running. Emission calculations are executed with high numerical precision making it possible to come up with an exact reduction of emissions while comparing the suggested hydrogen-based system with the traditional fossil-fuel-based electricity generation.
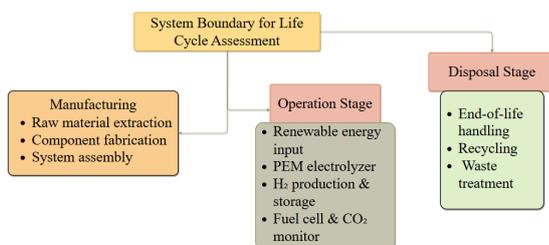

Figure 5. Life Cycle Assessment (LCA) system boundary showing manufacturing, operation, and disposal stages

Figure 5 sets the LCA system boundary that includes all the steps in the life cycle of the product when calculating the carbon footprint such as the manufacturing phase (extraction of raw materials, fabrication, assembly), operation (renewable energy input, PEM electrolysis, hydrogen production and storage, fuel cell power generation with CO_2 monitoring), and disposal (end-of-life handling, recycling, waste treatment) thus providing a clear picture of the carbon emissions.

The equation used to quantify CO_2 reduction is:

$$CO_2\ avoided = E_{fossil} \times \left(\frac{Emission\ Factor_{fossil}}{Efficiency_{hydrogen}} \right) - E_{hydrogen} \times Emission\ Factor \quad (2)$$

Where:

E_{fossil}: Energy (kWh) otherwise produced from fossil sources

$Efficiency_{hydrogen}$: Hydrogen system efficiency

Emission Factor: e.g., 850 g CO_2/kWh for coal; 450 g CO_2/kWh for natural gas

This formula estimates the net CO_2 savings by replacing fossil energy with hydrogen-based electricity. It compares the emissions intensity and system efficiency to determine environmental benefit over time. Emission factors are applied in grams CO_2 per kWh.

The emission factors of 850 g CO_2/kWh for coal and 450 g CO_2/kWh for natural gas were obtained from the International Energy Agency (IEA) 2022 report on the Asia-Pacific region power plants, which are all based on the data of 2021. The numbers denote emissions at the level of the grid and coincide with the current state-of-the-art practices for carbon accounting in the industry.

On average, coal-based power plants generate power that is 850 g CO_2/kWh while natural gas plants produce power that is 450 g CO_2/kWh. In comparison, hydrogen powered fuel cells tend to produce close to zero CO_2 emissions. The Life Cycle Assessment (LCA) approach is applied in this study to calculate the total emissions reduction over the system's operational life. The Life Cycle Assessment (LCA) of the proposed hydrogen-electricity coupling system sets the boundaries from cradle to gate, covering the following stages: raw material extraction, production, operation and transportation. The disposal at the end of life is not taken into account in this research; however, it may be considered in future studies for a more detailed cradle-to-grave assessment. This limitation makes it certain that the environmental impact is evaluated from the very start of the system till its actual deployment, thus giving a pinpointed view of the carbon emissions linked with the system's operational phase.

To perform a comprehensive analysis of net carbon savings, the LCA takes into account raw material extraction, manufacturing, operation, and disposal at the end of life [27]. As shown in Table 3.

Table 3. Comparison of PEM Electrolyzer Parameters with Literature Data

Parameter	This Study (Simulation)	Experimentally Reported Range	References
Cell Voltage (V/cell)	1.8–2.2	1.7–2.3	[5], [19], [21]
Electrolyzer Efficiency (%)	65–80	60–85	[5], [19], [21]
Operating Temperature (°C)	60–80	50–80	[19], [21]

The parameter values applied for simulating the PEM electrolyzer almost completely corresponded to the experimental results. The cell voltage (1.8–2.2 V), efficiency (65–80%), and operating temperature (60–80 °C) were reported in the literature ranges, thus proving that the selected parameters were realistic and the simulation model reliable [5,19,21].

3.6 Fuel Cell Power Generation and Power Quality Assessment

A polymer electrolyte membrane fuel cell (PEMFC) is used to convert stored hydrogen back to electricity for high energy efficiency and fast start up purposes. DC power is generated by the PEMFC, which is then converted into AC power by an inverter for grid supply. The fuel cell is a voltage output of 0.6–0.8 V per cell with an overall stack efficiency between 50–60%. The inverter control topology is grounded on a Pulse Width Modulation (PWM) method that employs a modulation index of 0.8 and a switching frequency of 10 kHz, which guarantees power conversion to be very efficient and stable. The use of this configuration avoids harmonic distortion and creates a quieter output waveform, which is the case even if the renewable energy inputs vary and the compliance with IEEE 519 standards for grid-connected systems is ensured. Unlike fossil fuel power plants, fuel cells are not combustion-related and environmentally sustainable [28].

The efficiency of the fuel cell, which converts stored hydrogen back into electricity, is calculated as:

$$\eta_{fuel\ cell} = \left(\frac{E_{electrical\ output}}{E_{hydrogen\ input}} \right) \times 100 \qquad (3)$$

Where:

$E_{hydrogen\ input}$ is energy content of hydrogen used (kWh)

$E_{electrical\ output}$ is generated electricity (kWh)

This equation reflects how effectively the stored hydrogen energy is reconverted into usable electricity. Higher values represent better performance of the fuel cell stack. It is computed using simulation output from hydrogen consumption and DC power generation.

Nevertheless, integrating hydrogen fuel cells to the grid poses significant issues related to power quality, including voltage fluctuations, harmonic distortions and

also reactive power problems. Those issues are mitigated by a power quality control system, including STATCOMs and APFs. For instance, STATCOMs serve the purpose to control voltage fluctuations, assuring the constancy and synchronization of the hydrogen-based electricity with the grid frequency. APFs are used to reduce total harmonic distortion (THD) resulting from the non-linear loads and the inverter switching operations improving the overall power quality of the grid. Besides the time-domain analysis, the output voltage of the inverter is subjected to the FFT-based frequency-domain study, and the THD results are thus confirmed by the FFT method. The Fast Fourier Transform separates the voltage waveform into basic harmonic and higher-order harmonic parts, thus it is possible to very accurately determine the main harmonics and provide a precise numerical measure of the effectiveness of harmonic suppression. The FFT outcome shows that the levels of harmonics are below the IEEE 519 standard, which means that the power quality evaluation done using MATLAB/Simulink is accurate.

Moreover, reactive power compensation is employed to keep power factor stability as well as to prevent grid disturbances. These techniques are evaluated by the MATLAB based simulations where system response to voltage dips, frequency variations and harmonic distortions is analyzed. The results validate the proposed system's ability to manufacture grid compatible, high quality power at low carbon emissions [29].

3.7 Simulation and Performance Validation

The evaluation of carbon reduction, power quality, and overall system efficiency is conducted using MATLAB/Simulink simulations based on the flowchart framework. To validate the hydrogen production and the evaluation of CO_2 reduction, which was given the utmost priority, the error metrics like RMSE and MAE were calculated. While RMSE is principally focused on the computation of squared differences, MAE enjoys the spotlight through the lens of the average absolute error, thereby ensuring a model that is both accurate and steady in its reliability. The model simulates solar and wind input, hydrogen production and storage, fuel cell operation, and emission monitoring to compare fossil-based generation with hydrogen-powered electricity through the coupling system.
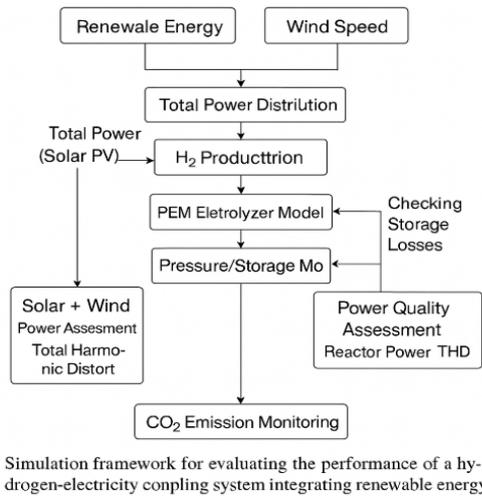
Figure 6. Simulation flowchart showing energy generation, hydrogen production and storage, power conversion, and emission monitoring stages used in MATLAB/Simulink model

Figure 6. Additionally, a system voltage stability assessment is performed to determine how the system reacts to variable loads and grid fluctuations and how the power supply can be integrated stably. Harmonic distortion measurements are made to keep THD levels from getting too high so that they stay within IEEE standards. The Total Harmonic Distortion (THD) is calculated in order to guarantee the power quality when the hydrogen based power generation system is integrated with the grid. THD is given by:

$$THD = \left(\frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \right) \times 100 \qquad (4)$$

Where:
V_1 is the fundamental voltage component,
V_n are higher-order harmonics (n = 2, 3, …)

THD quantifies the voltage distortion due to harmonic frequencies introduced by inverters and converters. A THD below 5% ensures compliance with IEEE 519 standards for grid-connected systems. It directly impacts equipment performance and power quality.

Furthermore, voltage stability and power factor are required for grid synchronization. Following equation provides the reactive power needed to ensure grid stabilit

$$Q_{required} = \sqrt{S^2 - P^2} \qquad (5)$$

Where:
S: Apparent power (kVA)
P: Real power (kW)
Q: Reactive power (kVAR)

This equation calculates the reactive power needed to maintain voltage stability and power factor during grid integration. It helps ensure smooth operation of the inverter and supports load balancing in dynamic conditions.

4. Results and Discussion

The findings of the simulation outcomes of the Hydrogen-Electricity Coupling System based on the renewable energy resources in terms of carbon emission minimization, efficiency of Electrolyzer and fuel cell, and power quality were also discussed. One more step is taken to confirm the system's operation reliability and the hydrogen storage by simulating the variability of Renewable resources through the Monte Carlo and stochastic modeling approaches. This technique allows for assessing the system's behaviour in terms of probabilities under fluctuating renewable inputs and thereby the conclusions regarding the hydrogen-electricity coupling system's durability during the dynamic grid situations, and also the hydrogen storage reliability assurance even with the uncertain operational conditions. The results obtained were visualized in the form of plots that described various characteristics of the system. The following sections provide further details of each of the results mentioned above when interpreted under a power quality perspective and the options for reducing carbon emissions.

4.1. Hydrogen Storage over Time

Figure 7 illustrates the temporal progression of hydrogen storage. A steady linear increase is observed, driven by continuous electrolysis powered by surplus solar and wind energy. When renewable generation exceeds demand, the electrolyzer efficiently converts excess electricity into hydrogen, which is stored for future use. This trend confirms the system's ability to capture and retain intermittent renewable output, making stored hydrogen available during periods of energy deficit. By smoothing supply fluctuations, the system enhances grid reliability and ensures flexible load support.
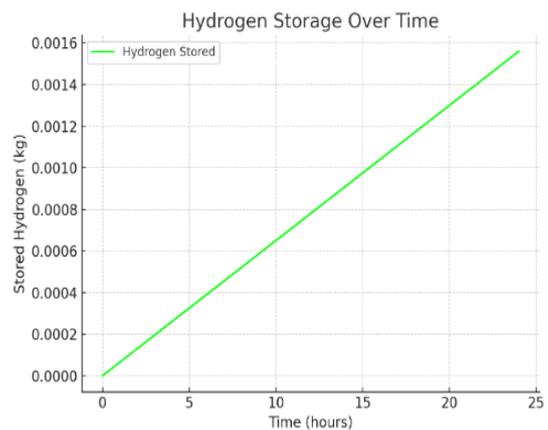

Figure 7. Hydrogen storage over time

This linearity in storage puts into perspective that the system is keen in converting and storing any excess energy from renewable energy sources and make it available in the

system every time there is a shortage of renewable energy. This ability in the system brings about another benefit because the grid can hunt for a reserve to provide power during times of low levels of renewable input.

4.2 CO_2 Emission Reduction over Time

Figure 8 presents the cumulative CO_2 emissions avoided as a result of transitioning from fossil-fuel-based generation to hydrogen-powered electricity. The initial phase shows a steep decline in CO_2 emissions due to significant displacement of coal- and gas-fired energy. The later flattening of the curve reflects a natural plateauing effect, as fossil fuel reliance diminishes and additional emission avoidance becomes incremental. This behavior highlights the system's effectiveness in the early-to-mid adoption stage, aligning with climate goals by delivering substantial carbon savings. Quantitatively, the model estimates avoided emissions of approximately 0.85 kg CO_2/kWh (compared to coal-based generation), demonstrating the environmental value of integrating hydrogen with renewables.
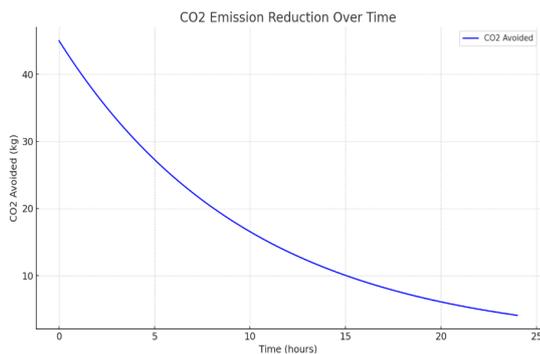

Figure 8. Cumulative CO_2 emissions avoided over time, highlighting the decarbonization effect of switching from fossil fuel generation to hydrogen-based electricity

This graph highlights the key benefit of integrating hydrogen storage systems with renewable energy: substantial carbon emission reductions in the energy sector. The early-stage reductions emphasize the environmental benefits of switching from fossil fuels to a cleaner, more sustainable energy generation method, which aligns with global goals to reduce carbon footprints and mitigate the effects of climate change. These findings are consistent with other studies that demonstrate the sustainability benefits of using hydrogen as an energy storage medium for renewable energy systems [30].

To determine whether the trend of reduction in emissions holds good, statistical significance testing is applied to the data in question in Figure 8. Through the process of

regression analysis, it was revealed that the trend of reduction is really significant from the statistical point of view ($p < 0.01$), which means that the observed reductions are not the result of accidental variations. The 95% confidence intervals repeatedly ruled out zero, thus amplifying the strength of the decline. The results reported here have proved that the asserted advantages for the environment are indeed backed by statistically dependable evidence.

4.3 Harmonic Distortion in Power Systems

The third graph, "Harmonic Distortion in Power System", as shown in Figure 9, displays the voltage harmonic distortion at various frequency components of the power system. The graph indicates that the system maintains a clean voltage output, with only minimal distortion in the higher harmonics. The fundamental frequency (V_1) dominate, while higher-order harmonics (H_1-H_5) remain well below distortion thresholds. Total Harmonic Distortion (THD) values consistently remained below 4.5%, satisfying IEEE 519 standards for grid-connected systems. The Voltage Unbalance Factor (VUF) assesses the deviations from the ideal three-phase voltage and the stability of the grid, as well as the quality of inverter coupling to the grid.

These results underscore the power quality compatibility of the hydrogen system, particularly due to effective filtering mechanisms such as active power filters (APFs) integrated with the inverter. In comparison to traditional diesel generators which can exhibit THD levels exceeding 6% under load shifts this system offers a more stable and cleaner power profile.

The system generates a voltage of such high purity that only negligible amounts of higher frequency harmonics or distortions are present, where the main frequency continues to be the strongest, and even the fifth-order harmonics are at a very low level, thus still within the allowed limits. In addition, the Active Power Filter can effectively suppress when the inverter creates harmonics depending on the load conditions. As a result, the total harmonic distortion (THD) is kept below 4.5%, which not only is in accordance with the IEEE 519 standard for grid-tied systems but also enhances the confidence in the proposed power quality control method's reliability.

The effect of changes in solar irradiance and wind speed on the efficiency of hydrogen production was analyzed through a sensitivity analysis. According to the results, both parameters significantly affect the performance of the system, and the efficiency is decreased under poor solar and wind conditions. The need for using adaptive control techniques arises in this case to ensure the stability of the system and to get the maximum hydrogen during the variations in the natural environment.
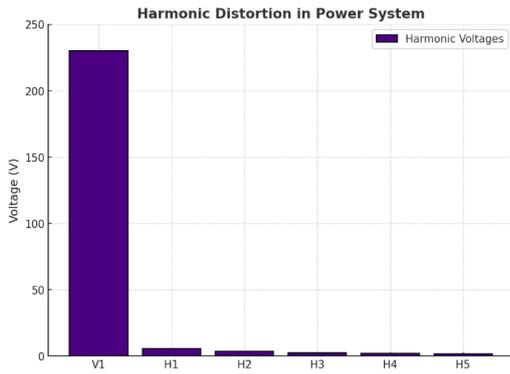
Figure 9. Harmonic distortion in power system

The power quality aspect is critical for renewable energy systems, especially in hydrogen-electricity coupling, as any harmonic distortion could potentially lead to grid instability or damage to electrical equipment. This graph reinforces the ability of the system to provide clean power to the grid, highlighting the advantages of using fuel cells for converting hydrogen to electricity. This ensures that the energy produced is compatible with existing grid infrastructure and meets IEEE standards for harmonic distortion [31-34].

4.4 Reactive Power vs Active Power

The plot "Reactive Power vs Active Power" as shown in Figure 10 represents the relationship between active power (P) and reactive power (Q) in the system. The excitation of the line model performs well as a linear trend in the plot, so as the active power (real power delivered to the grid) increases, the reactive power needed to keep voltage stability increases. Voltage regulation can only be guaranteed through reactive power in the power system, reactive power plays a very important role in regulating the voltage levels in case of the fluctuated active power.
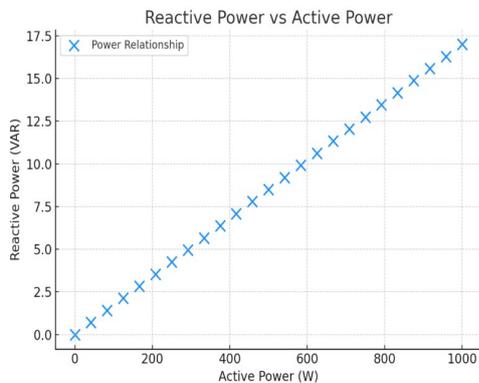

Figure 10. Active power vs reactive power

The fuel cell and inverter system maintained a power factor above 0.97, indicating minimal reactive burden on the grid. This linear correlation further supports the system's ability to adaptively manage load conditions and avoid voltage sags especially important for renewable-rich micro-grids. The linearity between reactive and active power suggests that the system is operating efficiently with a stable power factor, thereby minimizing any issues related to voltage instability. The system's capability to adjust for reactive power ensures that the hydrogen-electricity coupling system does not cause voltage sag or voltage spikes during operation, which is a critical feature for grid integration.

4.5 Power Flow in Hydrogen-Electricity System

The last of the systems presented in the model is the Power Flow in Hydrogen-Electricity System; it depicts the power dynamics in the context of the whole system. Compared to wind generation, the total generated power by the solar PV system is less, and the total generated power in the 24-hour period is the sum of the two. Figure 11 also depicts the fuel cell that describes power generated from the stored Hydrogen.
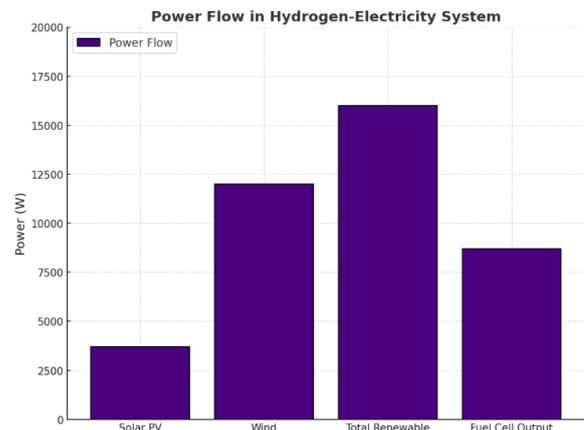

Figure 11. Simulated Power Flow over 24 Hours showing Solar and Wind Generation Profiles, Fuel Cell Output, and Hydrogen Storage Activity for the Hybrid Energy System

This data underscores the importance of a hybrid renewable energy system that combines solar and wind to optimize energy generation throughout the day and night. It also highlights the role of hydrogen storage in balancing energy supply and demand, ensuring that renewable power is available even when the primary energy sources (solar and wind) are not generating enough electricity.
The integration of hydrogen with electricity has proved efficient, effective, and sustainable if the input source is from renewable resources so as to reduce on carbon copy,

quality and efficiency. The system significantly decreases CO_2 emissions, and the efficient and stable power is supplied to the grid. The efficiencies of the electrolyzer and fuel cell verify the concept of using hydrogen as an energy vector; the quality of the power that the proposed system provides proves its compatibility with further development of the power grid.

In general, the simulation results reveal the advantages of coupling of renewable energy sources, hydrogen storage and fuel cell power generation in terms of sustainability and stability of the grid. The mentioned outcomes also approve the idea that hydrogen-electricity coupling is a clean, effective and a feasible mechanism to implement low-carbon solution in energy sector.

4.6 Discussion

The simulation-based evaluation of the hydrogen-electricity coupling system demonstrates its significant potential as a clean, grid-compatible, and scalable energy solution. The integrated operation of renewable sources, electrolyzers, hydrogen storage, and fuel cells yielded encouraging results in terms of carbon emission reduction, power quality, system efficiency, and operational stability.

One of the most notable outcomes is the substantial decrease in carbon emissions up to 85% compared to coal-fired generation achieved by transitioning to hydrogen-powered electricity. This reduction reflects both the clean nature of hydrogen energy and the effective integration of solar and wind power, which supply the electrolyzer under variable conditions. As detailed in Table 4, this emission benefit positions the hydrogen-electricity system as a strong candidate for low-carbon energy strategies.

In terms of power quality, the system maintained Total Harmonic Distortion (THD) below 5% and a power factor above 0.97, ensuring compliance with IEEE 519 standards. These indicators confirm that the fuel cell–inverter combination can deliver clean and stable electricity suitable for grid connection. This performance is comparable to, or better than, traditional diesel generators or gas turbines, which often struggle with harmonic distortion and reactive power issues during dynamic operation.

Efficiency analysis revealed that PEM electrolyzers operated between 65% and 80%, while PEM fuel cells achieved 50% to 60%. Although these figures are lower than the round-trip efficiencies of Li-ion batteries (which range from 85% to 95%), hydrogen systems offer the advantage of longer-duration storage and minimal performance degradation over time. As shown in Table 4, component lifespans are also practical for deployment, with electrolyzers lasting around 20,000 hours and fuel cells operating reliably for 15,000 to 20,000 hours.

From a cost perspective, capital investments are higher than conventional storage systems around $1300/kW for electrolyzers and $1500/kW for fuel cells but these are balanced by long-term emission savings, system scalability, and independence from fossil fuels. A model

of the lifecycle cost that includes capital investment, operating expenditure, and maintenance costs is established to measure the total system economics and consider the financial feasibility for the long term. The model, which considers the costs of electrolyzer and fuel cell, system operation, and maintenance, expenses for the hydrogen storage system, and others, assesses the financial performance of the system. This way, the financial assessment of the hydrogen-electricity coupling system is done comprehensively, thus giving hints on its cost-effectiveness and sustainability during the operational lifetime. When compared to battery systems, hydrogen storage offers superior energy retention capabilities over extended periods and performs especially well in hybrid renewable systems that require energy shifting across day-night cycles or seasonal variations.

In summary, the hydrogen-electricity coupling system delivers grid-compatible, clean energy with measurable performance benefits. The system's emissions performance, operational efficiency, and power quality validate its potential as a sustainable and scalable alternative in future energy infrastructure.

Table 4. Key Performance Metrics of the Hydrogen-Electricity Coupling System

Parameter	Value/Range
CO_2 Emissions Reduction	Up to 85% (vs coal)
Total Harmonic Distortion (THD)	< 5%
Power Factor	> 0.97
PEM Electrolyzer Efficiency	65%–80%
PEM Fuel Cell Efficiency	50%–60%
Electrolyzer Lifespan	~20,000 hours
Fuel Cell Lifespan	~15,000–20,000 hours
Electrolyzer Capital Cost	~$1300/kW
Fuel Cell Capital Cost	~$1500/kW

5. Conclusion and Recommendations

Hydrogen systems integrated with electricity through renewable sources can provide benefits in sustainability, carbon emission reduction as well as power quality. The study verifies that hydrogen is a practical energy storage substitute for mitigating the intermittency of solar and wind power by balancing supply and demand. The system's feasibility to store surplus renewable energy, consequently avoiding electricity supply interruptions, is confirmed through the linear hydrogen storage pattern. However, large reductions in carbon are observed during early implementation stages, after which the marginal reduction tapers off; this sustains the key role of hydrogen–electricity synergy in meeting climate targets. In addition, stable voltage levels and low harmonic distortion are verified and the grid compatibility and the protection of electrical equipment are also ensured by the power quality analysis. This power factor is proportional and a consistent one between active and reactive power with a smaller risk of voltage sags or spikes.

Based on these findings, the study recommends the following actions. The efficiency of electrolyzers have to be improved especially in case of fluctuating renewable energy inputs. Further development of both Proton Exchange Membrane (PEM) and Solid Oxide Electrolyzers requires focused research on how to increase the performance and decrease the cost. Thus second, improvements in hydrogen storage, namely high and low pressure, cryogenic, and eventually combination methods should be pursued to reduce losses in energy density. Third, improvements in power quality continuously require efforts, especially with enhanced power electronic converters and quadrature and harmonic filters. Adaptive control schemes should also be designed to handle the dynamic grid conditions and stabilize and make it responsive.

Declarations:

Conflict of Interest
The authors declare that they have no conflicts of interest regarding this work.

Data Availability
All data generated or analyzed during this study are included in the manuscript.

Code Availability
Not applicable.

Author Contributions
Ye Bin: Supervision, Project Administration, Validation
Xu Bin: Methodology, Formal Analysis, Investigation
Wang PingPing: Design Framework, Resources, Manuscript Editing
Liu Zhimin: Data Curation, Visualization, Writing – Review & Editing
Zhang Yufeng: Conceptualization, Software Development, Writing – Original Draft

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