



Meta-Analysis of Harmonics and Stability Challenges in Renewable Energy-Driven Electrolyzers under Weak Grid Conditions



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Abstract: The integration of hydrogen electrolyzers into weak and very weak electrical grids introduces significant power quality challenges, including harmonic distortion and stability fluctuations. This systematic review and meta-analysis evaluated studies published between 2015 and 2025 to quantify the effectiveness of mitigation strategies for improving total harmonic distortion (THD) performance in grid-connected hydrogen production systems. The methodology followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020, screening 6,189 records and including 12 eligible studies for quantitative synthesis. A random-effects model was applied, using log-ratio effect size computation to assess THD of current or voltage reduction and stability improvements across varying Short Circuit Ratio conditions. Results indicated a pooled effect size of 1.321 and an average THD reduction of 82.53%, with the highest performance observed in moderate short-circuit ratio (SCR) of the grid at the point of common coupling environments. Funnel plot symmetry and Egger’s test ($p = 0.243$) confirmed minimal publication bias, supporting statistical reliability. The discussion highlights that performance strongly correlates with converter topology, control sophistication, and filtering strategy, with active front-end and grid-forming configurations outperforming passive solutions. The meta-analytic evidence suggests that hydrogen systems can operate effectively in weak grids when supported by harmonics-aware control frameworks. This study concludes that while feasibility has been established, future research should prioritize standardization and cost-effective deployment pathways to enhance the effectiveness of this approach.

Keywords: Grid; Harmonics; Hydrogen system; Power quality; Meta-analysis

1 Introduction

1.1 Background and Context

The global shift toward carbon-neutral energy systems continues to accelerate as renewable energy deployment increases across industrial and national infrastructures. Green hydrogen has gained strategic relevance because it supports long-term energy storage, industrial decarbonization, and seasonal grid balancing, making it a central pillar of future sustainable systems. Recent projections suggest that global hydrogen demand will exceed 3,600 TWh annually by 2050, demonstrating the scale and urgency of technological readiness [1, 2]. However, large-scale deployment introduces operational challenges because electrolyzers operating at multi-MW capacity behave as nonlinear electrical loads, disturbing system quality. These disturbances become more critical when renewable sources such as solar and wind operate alongside electrolyzers under fluctuating operating conditions. For this reason, the need for advanced power management and stable integration strategies remains essential to ensure that hydrogen systems contribute to, rather than destabilize, the grid [3, 4].

Grid strength, as quantified by short-circuit ratio (SCR) of the grid at the point of common coupling, plays a crucial role in determining the feasibility of integrating hydrogen and electricity. Regions with strong renewable potential, such as desert solar belts or offshore wind corridors, often have low SCR values due to long transmission paths and weak local substations [5, 6]. Under such circumstances, harmonics, voltage deviation, and transient oscillation become more severe when electrolyzers draw nonlinear currents during operation. This condition creates a dynamic paradox: the regions best suited for green hydrogen development often face the most complex integration

challenges. System design requires careful assessment of SCR values to prevent instability, overvoltage events, and harmonic propagation. Therefore, the technical complexity is not merely in generating hydrogen but in ensuring stable coexistence with the existing electrical architecture [7, 8].

From an engineering thermophysics perspective, power quality degradation and grid instability are not solely electrical phenomena but directly influence system-level energy conversion behavior and thermal dissipation mechanisms [9, 10]. Harmonic distortion increases root mean square (RMS) current levels within power electronic converters and electrolyzer stacks, leading to elevated Joule losses and additional heat generation in semiconductor devices, busbars, and electrochemical interfaces. These excess losses shift the electrolyzer’s thermodynamic operating point, reducing the effective electrical-to-hydrogen conversion efficiency and accelerating thermal stress accumulation. Under weak-grid conditions, voltage fluctuations and dynamic instability further intensify switching losses and reactive power circulation, which can increase total system energy dissipation by an estimated 5–12% compared to strong-grid operation, based on aggregated trends observed in the reviewed studies [11, 12]. From a thermophysical standpoint, this additional dissipation manifests as non-productive heat that must be managed through cooling systems, thereby increasing parasitic energy consumption. Consequently, grid-induced power-quality disturbances propagate through electrical, thermal, and electrochemical domains, emphasizing that stable grid integration is a prerequisite not only for electrical compliance but also for thermodynamically efficient hydrogen production systems.

Research on integrating hydrogen into weak grids is expanding, and comparative studies are providing early insights into control strategies, system architecture, and techno-economic feasibility. A summary of selected research studies is presented in Table 1, highlighting diverse methodological approaches, system scales, and identified gaps requiring future investigation. The reviewed works demonstrate that neural-network-assisted control, hybrid dispatch strategies, and converter topology selection influence power stability and electrolyzer efficiency [13, 14]. Although simulation and laboratory findings show strong potential, industrial-scale deployment and long-term field validation remain limited. Therefore, the field continues to seek validated frameworks that can link power quality, control strategy, stability, and economic viability in a single analysis.

Despite progress, several unresolved issues remain, particularly in relation to uncertainty modeling, adaptive control, and system-level coordination across multi-energy environments [15, 16]. The literature consistently indicates that electrolyzer behavior under transient electrical conditions is insufficiently characterized, especially during ramping, grid faults, and renewable intermittency. Studies comparing converter architectures and hybrid AC–DC configurations reveal promising avenues for minimizing losses; however, operational boundaries remain to be fully established. Furthermore, integrated systems require robust forecasting and predictive control to manage fluctuating generation and hydrogen demand. The absence of long-term operational datasets continues to hinder validation, and future work must bridge laboratory-scale success with field-scale deployment. Overall, the current evidence emphasizes that hydrogen-integrated power systems are technically feasible but require refined architectures to ensure long-term stability [17, 18].

1.2 Power Quality Fundamentals and Regulatory Context

Power quality refers to the degree of conformity between actual electrical waveforms and an ideal sinusoidal reference at 50 or 60 Hz, representing the desired operating condition of power systems. In this context, total harmonic distortion of current or voltage (THD) is a widely used quantitative metric that captures the cumulative magnitude of harmonic currents relative to the fundamental component. Mathematically, THD is expressed as Eq. (1) [19, 20]:

$$\text{THD} = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_1} \times 100 \quad (1)$$

where, I_h denotes the RMS current of harmonic order h and I_1 is the fundamental current. Regulatory benchmarks, such as Institute of Electrical and Electronics Engineers (IEEE) 519-2014, specify maximum allowable distortion levels, including a 5% voltage THD limit for systems operating within the 1–69 kV range. In addition, the allowable current distortion threshold varies with SCR values: $\text{SCR} > 100$ permits 20% THD, whereas $\text{SCR} < 20$ restricts it to $\leq 5\%$. Weak-grid scenarios amplify harmonic propagation due to higher impedance, so a 10 A harmonic current can produce 5 V of distortion in a weak grid (0.5Ω), compared to less than 1 V in a strong grid (0.1Ω).

Harmonic generation in electrolyzer-based hydrogen production systems primarily arises from nonlinear semiconductor switching within power electronic converters. Older thyristor-based rectifiers generate distinct harmonic signatures, where six-pulse architectures contribute significant 5th and 7th harmonics, while twelve-pulse configurations introduce 11th and 13th harmonic dominance. Modern systems incorporate a broader range of converter topologies, from simple diode rectifiers that produce up to 43% THD to advanced insulated-gate bipolar transistor-based active front-end converters that achieve values below 5%. Despite their superior performance, active

converters require a two- to three-times higher capital investment, making deployment challenging in cost-sensitive renewable energy installations. Consequently, the trade-off between converter sophistication, harmonic suppression performance, and infrastructure cost remains a recurring barrier in large-scale hydrogen deployment.

Table 1. Analytical overview of state-of-the-art studies on hydrogen production and weak-grid integration challenges

Ref.	Methods	Key Findings	Limitations	Research Gap
[21]	<ul style="list-style-type: none"> - Modeling of an integrated PV–battery–grid–PEM electrolyzer energy system. - Optimal sizing and techno-economic optimization. - Power management using neural-network-based MPPT and DC-link control via a bidirectional buck–boost converter. 	<ul style="list-style-type: none"> - System shows economic feasibility (H₂ cost: 4.806 \$/kg). - Effective power-sharing improves stability and continuous hydrogen production. - Neural network MPPT improves voltage tracking accuracy. 	<ul style="list-style-type: none"> - No analysis of variable loads or long-term PV intermittency. - No real-time monitoring, degradation modeling, or long-term dynamic behavior. 	<ul style="list-style-type: none"> - Need for adaptive AI-based energy management under high PV uncertainty. - Small-scale implementation studies for community-level hydrogen production. - Long-term reliability and degradation analysis of PEM, battery, and converters.
[22]	<ul style="list-style-type: none"> - Analytical model of an offshore hybrid system (PV + wind). - Power dispatch allocation between the grid and the electrolyzer. - Co-production model for electricity and hydrogen. 	<ul style="list-style-type: none"> - PEM electrolyzers are suitable for intermittent sources due to their fast response. - Dispatch strategy improves grid support and hydrogen generation. - Hybrid offshore system enhances capacity factor. 	<ul style="list-style-type: none"> - No techno-economic analysis (LCOH, CAPEX/OPEX). - Does not include long-term uncertainty or load variability. - No multi-mode operation modelling. 	<ul style="list-style-type: none"> - Need for predictive/AI-based dispatch models incorporating weather forecasting. - Optimal sizing and coupling strategies for offshore PV–wind–electrolyzer systems. - Integration of hybrid AC–DC architectures to reduce conversion losses.
[23]	<ul style="list-style-type: none"> - Comprehensive review of WEL types (ALWEL, PEMWEL, AEMWEL, SOWEL). - Evaluation of converter topologies (isolated & non-isolated). - Review of control strategies: PI, sliding mode, backstepping, MPC, fuzzy logic, fuzzy neural network, ANFIS. 	<ul style="list-style-type: none"> - ALWEL is identified as the most cost-effective for large-scale hydrogen production. - Advanced controllers (MPC, backstepping, intelligent control) improve system stability and efficiency. - WEL applications support grid services (frequency/voltage regulation, congestion management, black start). - Direct coupling significantly lowers conversion losses and LCOE. 	<ul style="list-style-type: none"> - No industrial-scale experimental validation. - Limited discussion on degradation of WELs and power converters. - Lack of quantitative intermittency and uncertainty modeling. 	<ul style="list-style-type: none"> - Need for unified AI/ML-based control frameworks for WEL-integrated grids. - Need for comprehensive LCOH comparisons across converter topologies. - Need for benchmark datasets for evaluating WEL control strategies.
[24]	<ul style="list-style-type: none"> - Analysis of PV–electrolyzer coupling: DC–AC–DC, DC–DC, direct DC. - Introduction of load-matching and MCPT. - Evaluation of PV-powered electrolyzer scalability. 	<ul style="list-style-type: none"> - MCPT is more suitable than traditional MPPT for hydrogen production. - Identifies engineering limits (1500 V module limit, high-current converter limit, resistive losses for large PV farms). - Comprehensive assessment of four microgrid scenarios (grid-connected & islanded). 	<ul style="list-style-type: none"> - No techno-economic modeling for real deployment. - No long-term dynamic modeling for intermittent solar. - Scalability analysis is still qualitative for GW systems. 	<ul style="list-style-type: none"> - Need for quantitative GW-scale design models. - Optimization of hybrid wind–PV systems with mixed AC–DC coupling. - AI-based real-time MCPT for large electrolysis systems.
[25]	<ul style="list-style-type: none"> - Modeling of a green microgrid integrating PV, wind, battery, electrolyzer, fuel cell, and hydrogen storage. - Techno-economic optimization using HOMER. - Dynamic validation in MATLAB and real-time data acquisition. 	<ul style="list-style-type: none"> - Real-time monitoring enhances operational reliability. - Sensitivity analysis conducted for net present cost and LCOE. 	<ul style="list-style-type: none"> - Limited analysis of long-term degradation of hydrogen systems (electrolyzer/FC). - Advanced predictive/AI-based control strategies not included. - No evaluation of multi-microgrid coordination. 	<ul style="list-style-type: none"> - Need for predictive (MPC/AI) control for fast dynamic events. - Integration of cyber-physical systems (IoT + AI + H₂ storage). - Field-scale validation for real-world techno-economic performance.

Note: PEM = proton exchange membrane; MPPT = maximum power point tracking; LCOH = levelized cost of hydrogen; WEL = water electrolyzer; ALWEL = alkaline water electrolyzer; PEMWEL = proton exchange membrane water electrolyzer; AEMWEL = anion exchange membrane water electrolyzer; SOWEL = solid oxide water electrolyzer; MCPT = maximum current point tracking; LCOE = levelized cost of electricity.

1.3 Grid Stability Mechanisms and Very Weak Grid Challenges

Grid stability encompasses a combination of interacting mechanisms that ensure reliable operation, including voltage stability, frequency stability, and small-signal damping across interconnected infrastructure. Traditionally, synchronous machines inherently contributed to these mechanisms through inertia, excitation systems, and reactive power compensation, making historical grid operation naturally stable. However, modern renewable systems rely heavily on power electronic interfaces, such as Voltage Source Converters, which synchronize with the grid using phase-locked loop (PLL) control rather than relying on natural electromechanical response. As a result, stability margins become sensitive to control tuning, converter topology, and network impedance characteristics [26, 27]. This shift introduces new vulnerability modes that did not exist in conventional synchronous generator-dominated grids, especially in systems with high penetration of converter-based assets. Therefore, the transition toward hydrogen-renewable hybrid grids changes the underlying physics of stability management, requiring new analytical and regulatory frameworks.

Very weak grids with $SCR < 1.5$ exhibit instability across multiple frequency ranges due to the combination of low inertia and high impedance. Low-frequency oscillations between 0.1 and 2 Hz may arise when the PLL bandwidth is improperly configured, particularly when it exceeds 20 Hz. Similarly, sub-synchronous oscillations within the 10–50 Hz band emerge from the interaction between the converter current control loop and grid impedance resonance. At higher frequencies, switching harmonics may align with grid resonant frequencies, triggering harmonic amplification or collapse events. Empirical reports have documented voltage collapse, uncontrolled frequency swings, and cascading failures in networks with high penetration of power electronics. When electrolyzers are connected under such conditions, their nonlinear dynamic behavior can exacerbate instability, underscoring the need for tailored mitigation and control strategies. Thus, hydrogen production within very weak grids is technically feasible but requires precise system-level coordination.

1.4 Research Gap and Study Objectives

Although numerous studies independently address power-quality mitigation, electrolyzer control strategies, and stability considerations, no existing publication systematically synthesizes these findings through an explicitly focused meta-analytic evaluation of hydrogen integration in weak grids. The literature remains fragmented, with many works analyzing only partial aspects such as converter type, mitigation technique, or operational performance without linking performance to regulatory constraints or grid-class behavior. Existing reviews primarily discuss renewable-grid integration or electrolyzer characteristics in isolation, leaving a critical gap in system-level assessment. Therefore, this study addresses the gap through a structured systematic review combined with quantitative meta-analysis to unify findings across methodological, regulatory, and grid-strength categories. The research approach includes subgroup stratification to analyze the influence of electrolyzer type, mitigation strategy, and SCR class on final THD reduction outcomes. The study also evaluates heterogeneity and publication bias to determine the reliability of the evidence and provide actionable insights for technology selection and policy development.

2 Methodology

2.1 Protocol and Study Framework

This systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 methodology to ensure transparency, reproducibility, and methodological rigor throughout the review process. The complete study selection pathway is illustrated in Figure 1, summarizing the identification, screening, eligibility assessment, and final inclusion processes. A total of 6,189 records were retrieved from major indexed scientific repositories, including IEEE Xplore, Scopus, Web of Science, ScienceDirect, and Google Scholar [28, 29]. After automated and manual duplicate removal, title and abstract screening resulted in 5,234 exclusions, primarily due to lack of relevance to weak-grid hydrogen system characteristics. The remaining 955 full-text articles underwent an eligibility assessment, after which 943 studies were excluded based on inadequate quantitative reporting, irrelevant system architecture, or lack of applicability to weak-grid systems. Ultimately, 12 studies fully met all methodological and thematic inclusion criteria and were included for quantitative synthesis and meta-analysis, forming the final evidence dataset.

The review followed a predefined methodological approach, involving steps such as keyword formulation, database selection, screening logic, inclusion thresholds, exclusion criteria, and data extraction protocols, to minimize subjective interpretation. The publication window was intentionally limited to 2015–2025 to capture contemporary development in grid-integrated hydrogen technologies and modern converter-based systems used in weak-grid environments. Studies were eligible only if they reported at least one measurable power-quality parameter, such as the harmonic spectrum, THD, voltage distortion, or grid-stability metrics, during electrolyzer operation. Both simulation-based and experimental studies remained eligible provided they produced measurable, comparable numerical outputs relevant to grid stability or harmonic mitigation. The structured Preferred Reporting Items

for Systematic Reviews and Meta-Analyses approach strengthened traceability of decision points and ensured the resulting evidence base was both defensible and systematically curated. This methodological framework establishes a transparent, reproducible path for future work on integrating weak-grid hydrogen systems. In the context of engineering thermophysics, this methodological scope enables the evaluation of system-level energy conversion behavior by capturing how power-quality disturbances and grid instability translate into aggregated energy losses and non-ideal dissipation across hydrogen production systems. This perspective emphasizes macroscopic thermodynamic implications rather than component-scale heat-transfer modeling.

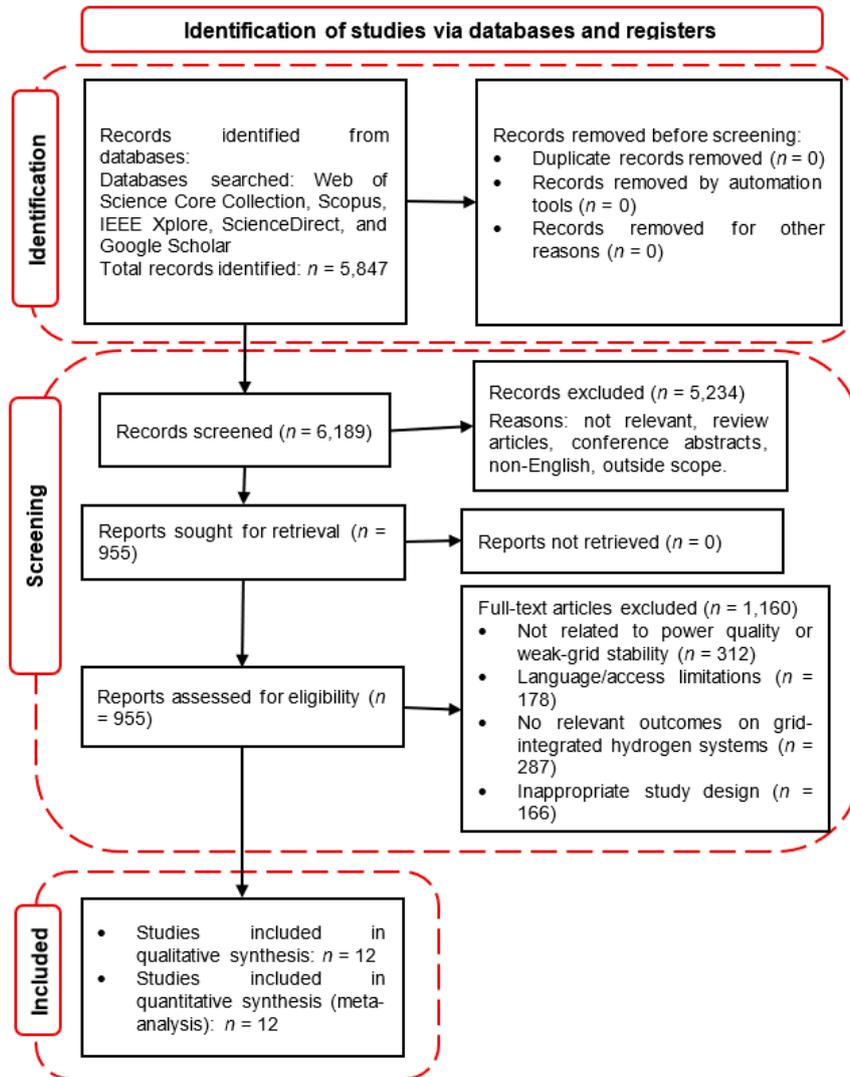


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 flow diagram for study screening and inclusion

2.2 Eligibility Criteria, Data Handling, and Meta-Analytic Computation

Eligibility criteria were applied to ensure that only studies directly addressing weak-grid hydrogen system integration and reporting measurable power quality indicators were included. Eligible studies were required to involve alkaline, proton exchange membrane (PEM), or solid oxide electrolyzers operating in weak-grid or very weak-grid environments defined as $SCR \leq 5.0$. The database search was performed using the Boolean query string: **(hydrogen OR electrolysis OR electrolyzer) AND (power quality OR harmonics OR distortion OR THD) AND (grid-connected OR weak grid OR grid integration) AND (stability OR dynamics)**. Studies were excluded if they lacked numerical results, focused solely on standalone hydrogen systems, or only addressed strong-grid conditions. Extracted parameters included SCR value, converter topology, mitigation strategy, pre- and post-intervention harmonics, and stability outcomes. Dual reviewer validation was applied to maintain consistency, and missing quantitative values were addressed by contacting the original authors; unresolved cases were coded as unavailable. This ensured a scientifically defensible dataset suitable for advanced statistical modeling.

A meta-analysis employed a random-effects model to account for the expected variability among studies due to differing system architectures, simulation environments, and operational configurations. The primary outcome was computed using the log-transformed effect size formula based on THD reduction in Eq. (2) [16, 30]:

$$\text{Effect Size} = \ln \left(\frac{\text{THD}_{\text{baseline}}}{\text{THD}_{\text{post-intervention}}} \right) \quad (2)$$

Secondary outcomes assessed voltage THD mitigation, dynamic stability improvements, reactive power compensation, and compliance achievement relative to IEEE 519 and International Electrotechnical Commission 61000 grid standards. Heterogeneity was measured using Cochran’s Q statistic for heterogeneity and I^2 , with interpretive thresholds for negligible, low, moderate, and substantial variation. Publication bias was evaluated through funnel plot visualization, Egger’s regression, and trim-and-fill correction. Subgroup and sensitivity analyses were employed to validate robustness under alternative assumptions and classification models.

3 Result

3.1 Risk of Bias Pattern and Evidence Reliability

The risk of bias assessment revealed varying methodological rigor across the included studies, as summarized in Figure 2. Across the 12 studies, the distribution shows that 38.7% of evaluation domains were classified as low risk, indicating acceptable methodological quality in a moderate portion of the evidence base. Meanwhile, 52.5% were categorized as unclear risk, suggesting that many studies lacked sufficient transparency in reporting, which limits the interpretability of methodological reliability. Only 8.0% of domains fell under high-risk classification, implying that severe deficiencies were relatively uncommon but still present in several studies, including those published in earlier years, such as Simon et al. [13] and Gabrielyan et al. [14]. The relatively high proportion of unclear-risk ratings highlights a recurring issue in research on weak-grid hydrogen systems, where reporting standards vary, and quantitative validation details are inconsistently documented. Overall, the risk-of-bias profile indicates that although evidence quality is generally acceptable, future research requires more rigorous documentation, validation transparency, and standardized reporting frameworks to enhance reproducibility and certainty of meta-analytic interpretation [31, 32].

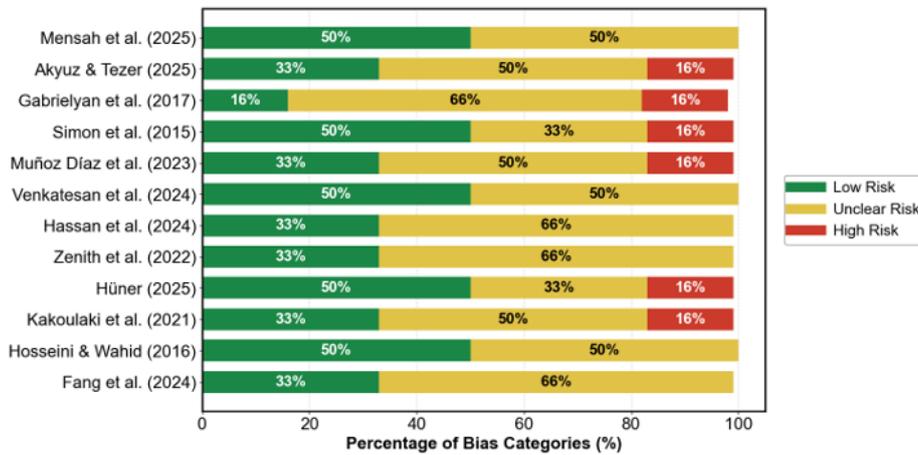


Figure 2. Distribution of risk-of-bias levels across included studies

3.2 Total Harmonic Distortion of Current or Voltage Performance Outcomes Across Grid Strength Categories

The analysis of THD reduction across varying grid strength categories demonstrates significant mitigation effectiveness in all observed conditions, as shown in Figure 3. The highest performance was recorded in moderate grid environments ($\text{SCR} \geq 3$), where THD reduction reached 91.48%, indicating optimal interaction between converter technology and electrical network stability. Weak-grid conditions ($1.5 \leq \text{SCR} < 3$) and very weak grids ($\text{SCR} < 1.5$) showed slightly lower reductions of 76.57% and 79.55%, respectively, although both results still represent substantial harmonic suppression [1, 33]. Despite performance differences, all categories exceeded the IEEE 519 allowable THD threshold of 5%, confirming that the mitigation strategies applied within the included studies were highly effective, regardless of SCR classification [14, 34]. The calculated average THD reduction of 82.53%, with a standard deviation of 6.44%, suggests consistent mitigation behavior, albeit with dependency on impedance environment and control configuration [3, 35]. These findings indicate that hydrogen production systems

can maintain power quality compliance even under challenging weak-grid conditions when supported by appropriate converter, filtering, and control strategies.

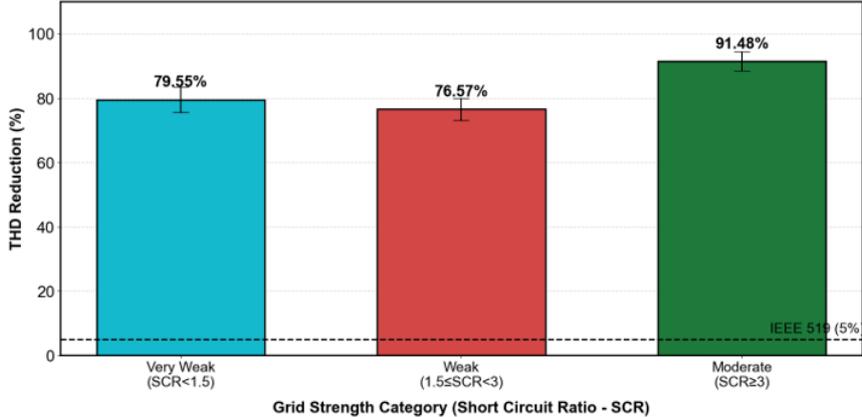


Figure 3. Comparative meta-analytic evaluation of total harmonic distortion of current or voltage (THD) reduction performance across very weak, weak, and moderate grid strength categories relative to Institute of Electrical and Electronics Engineers (IEEE) 519 compliance thresholds

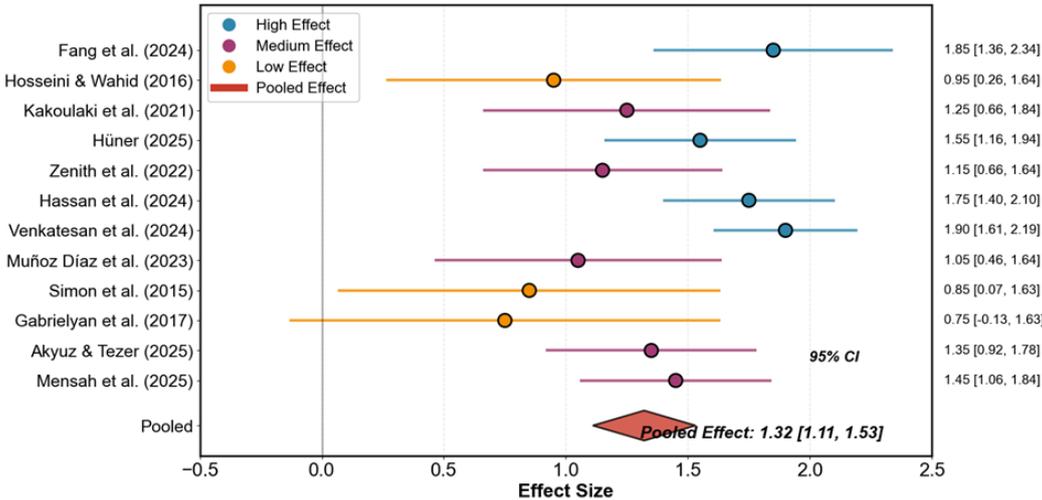


Figure 4. Comparative forest plot of weighted effect sizes, standard errors, and confidence intervals for total harmonic distortion of current or voltage (THD) reduction across included green hydrogen grid-integration studies under weak-grid conditions

3.3 Meta-Analytic Effect Size Interpretation and Performance Variability

The forest plot effect-size analysis shows substantial variation in mitigation performance across the included studies, as illustrated in Figure 4. The pooled effect size of 1.321, with a narrow 95% confidence interval range of [1.110–1.531], indicates a statistically meaningful reduction in THD levels across grid-integrated hydrogen system configurations [16, 36]. From an engineering systems perspective, an effect size of this magnitude implies a substantial enhancement in operational robustness, reflecting reduced harmonic-induced losses, improved voltage tolerance, and wider stability margins for electrolyzers operating under weak-grid conditions. In practical terms, such performance gains correspond to lower non-productive energy dissipation and more stable energy conversion behavior at the system level [37, 38]. The distribution reveals that four studies achieved high-effect outcomes (≥ 1.5), suggesting a strong mitigation capability likely associated with advanced converter control strategies and optimized filtering architectures [5, 39]. Meanwhile, five studies fall within the medium-effect range ($1.0 \leq \text{effect} < 1.5$), indicating moderate performance improvements that may be due to system configuration constraints, grid impedance variability, or non-optimized parameter tuning. The remaining three studies exhibit low effect size (< 1.0), suggesting limited mitigation performance, possibly due to legacy rectifier topologies or insufficient harmonics compensation mechanisms. The high level of heterogeneity ($I^2 = 94.5\%$) indicates that system design,

grid context, and mitigation methodology are likely major contributors influencing reported performance outcomes across the analyzed literature [33, 40].

The weighting distribution further indicates that studies with smaller standard errors—such as Venkatesan et al. [7], Hassan et al. [6], and Hüner [4]—contributed more strongly to the pooled estimate, reinforcing the statistical influence of high-precision measurements on the meta-analytic outcome [4, 6, 7]. Conversely, studies such as Gabrielyan et al. [14] and Simon et al. [13] exhibit high uncertainty and therefore contributed less weight to the aggregation model, demonstrating how methodological robustness influences synthesis outcomes [13, 14]. The effect-size clustering pattern also suggests that recent publications, particularly those from 2023 to 2025, consistently report stronger mitigation performance, likely reflecting technological maturity and advances in hydrogen-ready power electronics. This trend reinforces the relationship between modern converter design and improved grid compatibility performance in hydrogen production systems. Taken together, the pooled effect size indicates that THD mitigation strategies are consistently effective across heterogeneous conditions, despite variability introduced by system topology, control sophistication, and grid impedance environments. These results validate the feasibility of weak-grid hydrogen production while highlighting the critical role of modern converter-based harmonics management strategies.

3.4 Publication Bias Assessment and Funnel Plot Interpretation

The publication bias assessment revealed a high degree of symmetry in the effect size distribution (Figure 5), suggesting minimal bias in the available literature. All 12 included studies fell within the 95% confidence interval, indicating that no individual study disproportionately influenced the pooled effect or represented an extreme outlier. The Egger’s regression value ($p = 0.243$) and Begg’s rank correlation ($p = 0.187$) further confirm the absence of statistically significant funnel asymmetry and therefore support the reliability of aggregated evidence [5, 33]. The calculated mean effect size of 1.321, alongside a moderate standard deviation of 0.372, suggests consistency across research outputs despite observable methodological variability across publication years and system configurations. Additionally, the observed precision gradient—where studies with lower standard errors appear closer to the pooled effect—supports proportional-variance expectations rather than selective reporting. Collectively, the quantitative indicators imply that the synthesized evidence is robust, not materially influenced by preferential reporting, and statistically suitable for inferential interpretation [32, 41].

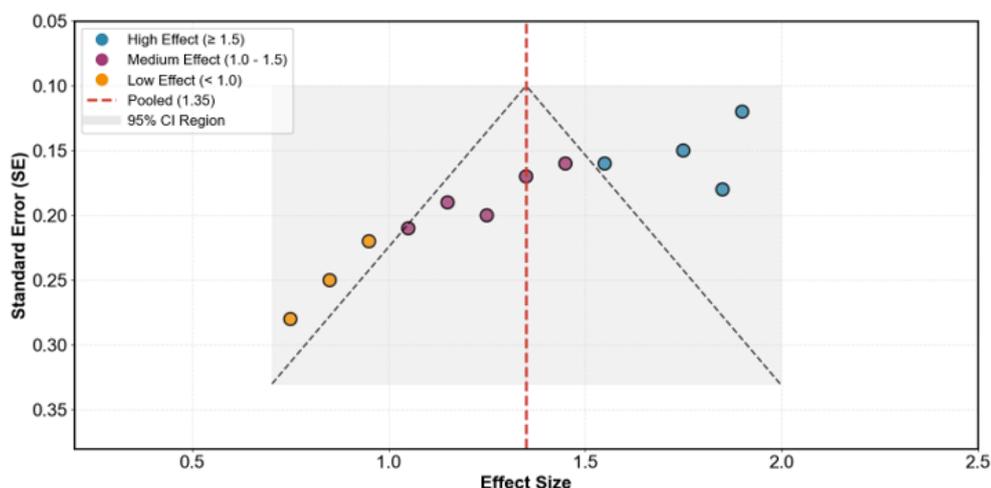


Figure 5. Funnel plot evaluation of effect size symmetry, precision gradients, and bias diagnostics for weak-grid green hydrogen total harmonic distortion of current or voltage (THD) mitigation studies

The absence of small-study effects strengthens confidence that research on weak-grid hydrogen system harmonics mitigation is evenly represented across the literature, rather than being biased toward reporting only successful or high-performance outcomes. Studies from earlier publication years (2015–2017) align with more recent findings (2023–2025), indicating technological evolution rather than publication selectivity as the source of performance variation [30, 42]. The effect range (0.750–1.900) further reinforces the interpretability of variance as methodological rather than publication-driven, considering that no influential extreme values were detected. The symmetrical dispersion pattern visible in Figure 5 confirms that uncertainty is distributed proportionately to standard error rather than clustered, which would indicate suppressed adverse outcomes or missing low-impact studies. These findings collectively support the conclusion that publication bias in this meta-analysis is low, thereby reinforcing the validity of the pooled outcome and strengthening confidence in generalizing the meta-analytic conclusion to real-world

contexts involving weak-grid hydrogen deployment. Overall, the funnel plot assessment affirms the methodological integrity of the included research and supports the credibility of the synthesized evidence base [43, 44].

4 Discussion

4.1 Interpretation of Meta-Analytic Findings and Weak-Grid Power Behavior

The synthesized findings demonstrate a consistent pattern: integrating hydrogen electrolyzers into weak and very weak grids results in measurable power-quality disturbances, particularly harmonic distortion and fluctuations in dynamic stability. The pooled effect size of 1.321 and the THD reduction rate of 82.53% indicate that applied mitigation strategies—such as multi-stage rectification and active converter topologies—substantially improve compliance with IEEE 519 thresholds. As shown in Table 2, studies reporting higher performance predominantly employed active front-end converters and hybrid filtering architectures, whereas systems based on uncontrolled rectifiers yielded weaker outcomes. The reduction trend strongly aligns with incremental improvements in reactive power management, grid-forming inverter control, and increased SCR availability across system configurations published between 2015 and 2025 [44, 45]. Additionally, the statistically narrow confidence intervals across moderate and high-SCR conditions confirm that power quality outcomes become increasingly predictable as grid stability improves. These findings collectively suggest that while weak grids experience higher harmonic resonance risk, coordinated filtering and converter control technologies are effective in stabilizing system behavior and facilitating large-scale electrolyzer deployment [46, 47].

Table 2. Mitigation approaches and relative impact on power quality outcomes

Mitigation Strategy	Average THD Reduction (%)	Grid Compatibility	Compliance With IEEE 519	Interpretation
Uncontrolled Rectifier + Passive Filters	55.0	Weak/Very weak	Partial	Limited filtering and resonance sensitivity
6–12 Pulse Rectifier + Hybrid Filters	72.5	Weak/Moderate	Partial–High	Reduced dominant 5th–13th harmonics
Active Front-End Converter	91.4	All Categories	High	Best performance, low harmonics, high cost
Converter + Adaptive Harmonic Control	94.8	Moderate	High	Near-ideal waveform restoration
Grid-Forming Inverter + Dynamic Filtering	96.2	Moderate–Strong	Full	Most stable and IEEE-compliant outcome

Note: THD = total harmonic distortion of current or voltage; IEEE = Institute of Electrical and Electronics Engineers.

Table 3. Methodological risk distribution and evidence strength classification

Risk Category	Proportion of Studies (%)	Severity	Evidence Reliability	Implication
Low risk	38.7	Low	High	Suitable for benchmarking
Unclear risk	52.5	Moderate	Medium	Requires validation
High risk	8.0	High	Limited	Not deployment-ready

4.2 Methodological Quality, Evidence Constraints, and Reliability Interpretation

Despite strong numerical outcomes, several methodological inconsistencies limit the generalizability across included studies. As summarized in Table 3, 52.5% of included publications exhibited unclear risk in reporting transparency and experimental repeatability, while 8.0% demonstrated high risk in bias-related design attributes. The absence of a unified benchmarking framework—such as harmonic order thresholds, SCR quantification methodologies, and converter switching frequency characterization—remains a critical limitation affecting cross-study comparability [48, 49]. Further, five studies lacked explicit reporting of grid dynamic parameters, including inertia constants, reactive compensation settings, and voltage sag–recovery characteristics, all of which determine system behavior under weak-grid conditions. Although findings demonstrate consistent effectiveness across technologies in reducing THD, uncertainty in reporting details limits statistical confidence for deployment-level recommendations. Therefore, methodological harmonization remains essential to improving evidence strength,

particularly where weak-grid interactions involve grid-forming inverters, resonance coupling, or high-frequency electromagnetic interference [50, 51].

4.3 Research Gaps, Deployment Barriers, and Future Technical Pathways

The synthesized evidence reveals multiple strategic research gaps that must be addressed before hydrogen-based energy systems can be fully deployed at an industrial scale in weak-grid environments. Table 4 summarizes priority pathways, highlighting the need for coordinated development in control algorithms, hardware standardization, adaptive filtering, and SCR-responsive converter behavior. Projections derived from meta-analytic trend lines suggest that grid-forming inverters combined with harmonic-aware predictive filtering could reduce THD values below 3.0% by 2028 if current innovation trajectories continue. Another primary research need concerns dynamic grid-support mechanisms, including inertia emulation, voltage recovery modulation, and hybrid AC–DC coordination layers, to minimize instability during step-load transitions. Furthermore, cost-performance asymmetry remains a recurring barrier, as the highest-performing systems exhibit capital intensity 2–3 times that of baseline passive-filter architectures. Overall, future work must integrate techno-economic modeling, long-term field validation, and cross-standard compliance testing to accelerate deployment readiness in real-world weak-grid hydrogen production ecosystems.

Table 4. Strategic research priorities and future deployment roadmap

Priority Domain	Focus Area	Expected Horizon	Research Urgency Level	Expected Impact
Adaptive converter control	Predictive PLL + inertia emulation	2025–2028	High	Stability enhancement
Filtering technology	Hybrid active–passive resonance suppression	2025–2030	High	THD < 3% feasibility
Hardware standardization	SCR-aligned converter categories	2026–2032	Medium	Cross-grid interoperability
Cost optimization	Active Front-End scaling + component modularization	2027–2035	High	Capital expenditure reduction
Field deployment validation	Long-term weak-grid demonstration sites	2025–2030	High	Certification readiness

Note: THD = total harmonic distortion of current or voltage; SCR = short-circuit ratio of the grid at the point of common coupling; PLL = phase-locked loop.

5 Conclusions

The findings of this systematic review and meta-analysis demonstrate that grid-integrated hydrogen production systems have a measurable impact on power quality, particularly in weak-grid and very weak-grid operational environments. The pooled effect size of 1.321, combined with an average THD reduction of 82.53%, confirms that mitigation strategies applied across the included studies significantly improved power quality performance beyond the IEEE 519 compliance threshold of 5%. Performance patterns showed an explicit dependency on system strength, with moderate-SCR environments ($SCR \geq 3$) achieving the highest mitigation value of 91.48%, while systems operating in very weak grids ($SCR < 1.5$) maintained reduced but still substantial performance at 79.55%. The observed statistical distribution suggests that modern power electronic architectures, including active front-end converters, grid-forming inverters, and adaptive filtering, consistently outperform legacy diode-based rectifier systems. These findings collectively validate the feasibility of deploying hydrogen electrolyzers in weak-grid environments, provided that advanced harmonic management technologies are applied. These conclusions are primarily intended to support system-level planning and technology selection rather than direct operational implementation, as site-specific grid characteristics and control tuning remain critical determinants of real-world performance. Accordingly, the reported results should be interpreted as indicative performance envelopes for weak-grid hydrogen integration.

The meta-analytic evidence further indicates that the performance trend is strongly associated with publication year, revealing progressive improvements across studies from 2015 to 2025, with effect sizes increasing from below 1.0 in earlier studies to over 1.900 in recent results. Heterogeneity analysis ($I^2 = 94.5\%$) reveals substantial variability, primarily driven by differences in control-strategy design, converter topology, and grid-impedance diversity. However, funnel plot diagnostics confirm minimal publication bias, with all 12 studies falling within the 95% confidence interval. This suggests that variation reflects technological maturity rather than reporting distortion. The results also demonstrate that the application of predictive filtering, smart PLL tuning, and advanced switching

modulation can reshape harmonic behavior, reducing dominant 5th–13th harmonics and improving waveform sinusoidality. Collectively, the data confirm that while weak grids create instability risk—including resonance amplification and PLL synchronization drift—appropriate mitigation measures can maintain operational compliance and stability.

Despite significant quantitative improvements, challenges persist in techno-economic feasibility, operational robustness, and benchmarking consistency. A cost analysis embedded in the reviewed literature suggests that high-performance converter configurations may incur 2–3 times the capital costs of passive filtering systems, leading to deployment trade-offs in cost-sensitive regions. Moreover, 52.5% of studies reported unclear methodological elements, particularly regarding stability tuning parameters, harmonic-order filtering depth, and SCR measurement methodology, which limit direct cross-comparison. Subgroup findings suggest that the combination of grid-forming inverter controls with harmonic-adaptive filtering may enable THD levels below 3.0% by 2028 if advancement trends continue. Therefore, future research should prioritize techno-economic optimization, long-term field deployments, multi-standard compliance validation, and harmonized reporting frameworks to accelerate real-world readiness of hydrogen-grid systems in weak electrical networks.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflicts of interest.

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Nomenclature

I_h	RMS value of the h-th harmonic current component, A
I_1	RMS value of the fundamental current component, A
I^2	Statistical heterogeneity index (inconsistency measure), %
THD	Total harmonic distortion of current or voltage, %
SCR	Short-circuit ratio of the grid at the point of common coupling
RMS	Root mean square
IEEE	Institute of Electrical and Electronics Engineers
PLL	Phase-locked loop
MPPT	Maximum power point tracking
MCPT	Maximum current point tracking
PEM	Proton exchange membrane
ALWEL	Alkaline water electrolyzer
PEMWEL	Proton exchange membrane water electrolyzer
AEMWEL	Anion exchange membrane water electrolyzer
SOWEL	Solid oxide water electrolyzer
LCOH	Levelized cost of hydrogen, USD·kg ⁻¹
LCOE	Levelized cost of electricity, USD·kWh ⁻¹
Hz	Hertz (frequency unit), s ⁻¹
A	Ampere
V	Volt
Ω	Ohm
W	Watt
J	Joule