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A TRADITIONAL LITERATURE REVIEW ON MODELING AND OPTIMIZATION OF SHUNT CURRENT REDUCTION IN LARGE-SCALE ALKALINE ELECTROLYZER (AEL) STACKS

Aqib Yaqub Awan[*1]

[*1]*PhD Scholar, U.S-Pakistan Centre for Advanced Studies in Energy (USPCAS-E), National University of Sciences & Technology (NUST), Sector H-12 Islamabad (44000), Pakistan.*

[*1]aqibyaqubawan@gmail.com

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Corresponding Author: *
Aqib Yaqub Awan

Abstract

Shunt currents represent a major parasitic loss mechanism in large-scale alkaline electrolyzer (AEL) stacks, adversely affecting electrical efficiency, current uniformity, component durability, and operational safety. As alkaline water electrolysis continues to play a critical role in large-scale hydrogen production, particularly in renewable energy–integrated systems, the mitigation of shunt currents has emerged as a key challenge in stack design and optimization. This traditional literature review systematically synthesizes existing research on the mechanisms, modeling approaches, and optimization strategies associated with shunt current reduction in large-scale AEL stacks, with a strong emphasis on numerical and multiphysics simulation methods. A comprehensive literature search was conducted in accordance with the PRISMA framework across major scientific databases, resulting in the selection of 56 peer-reviewed studies published between 2010 and 2025. The reviewed literature encompasses analytical models, numerical simulations, and fully coupled multiphysics approaches used to analyze current distribution, electrolyte conduction pathways, and stack-level electrical behavior. Particular attention is given to studies employing COMSOL Multiphysics, which has emerged as a widely adopted platform for simulating electrochemical, electrical, thermal, and fluid dynamic interactions within alkaline electrolyzer stacks. The findings indicate that shunt current magnitude is strongly influenced by stack geometry, manifold configuration, electrolyte conductivity, material properties, and operating conditions. Simulation-driven optimization strategies, including geometric redesign, electrical insulation, and flow-field modification, demonstrate significant potential for reducing parasitic current losses while maintaining hydrogen production efficiency. However, the literature reveals persistent gaps in large-scale experimental validation, standardized modeling practices, and integrated optimization frameworks. This review identifies key research trends, methodological limitations, and future research directions aimed at improving the efficiency, scalability, and long-term reliability of large-scale alkaline electrolyzer systems.

Introduction

Alkaline water electrolysis is one of the most established and commercially mature technologies for hydrogen production, particularly for large-scale industrial applications. Due to its relatively low capital cost, long operational lifetime, and tolerance to impurities, alkaline electrolyzer (AEL) systems have been widely deployed in chemical processing, energy storage, and power-to-gas applications (Zeng & Zhang, 2010; Ursúa et al., 2012). In the context of global decarbonization and increasing penetration of renewable energy sources, hydrogen produced via water electrolysis is considered a key energy carrier for achieving long-term sustainability targets (IEA, 2019; Buttler & Spliethoff, 2018). Among various electrolysis technologies, alkaline electrolyzers remain attractive for large-capacity installations due to their scalability and robustness under continuous operation. However, as the demand for higher hydrogen production rates increases, electrolyzer stacks are being designed with a larger number of cells operating at higher current densities. This upscaling introduces complex electrochemical, electrical, and fluid dynamic interactions that are not present in smaller systems. Consequently, non-ideal phenomena such as uneven current distribution, increased ohmic losses, and parasitic current pathways become more pronounced (Carmo et al., 2013). These challenges highlight the necessity for a detailed understanding of internal stack behavior, particularly with respect to electrical current flow. Among these issues, shunt currents have emerged as a critical limiting factor affecting the efficiency, durability, and safety of large-scale AEL stacks. Addressing these challenges requires a comprehensive synthesis of existing modeling and optimization studies, which forms the foundation of the present literature review.

Shunt currents are unintended electrical currents that flow through conductive electrolyte pathways outside the desired electrochemical reaction zones within an electrolyzer stack. In alkaline electrolyzers, these currents typically occur through electrolyte-filled manifolds, intercell gaps, and structural components that connect cells operating at different electrical potentials (Millet et al., 2011; Angulo et al., 2020). Unlike useful Faradaic currents that contribute directly to hydrogen production, shunt currents represent parasitic losses that reduce overall system efficiency. The presence of shunt currents leads to non-uniform current distribution across cells, resulting in voltage imbalances, localized overheating, and accelerated degradation of electrodes, diaphragms, and bipolar plates (Carmo et al., 2013; Bessarabov et al., 2016). In severe cases, shunt currents can induce corrosion in metallic components and increase the risk of gas crossover, compromising operational safety. The magnitude of shunt currents generally increases with stack size, electrolyte conductivity, and operating current, making them particularly problematic in large-scale AEL installations (Zhang et al., 2019). Despite their significance, shunt currents are difficult to measure experimentally due to the complex internal geometry of electrolyzer stacks and the inaccessibility of internal current paths. As a result, much of the understanding of shunt current behavior relies on theoretical and computational modeling. A comprehensive review of these modeling approaches is therefore essential for identifying dominant shunt current mechanisms and evaluating the effectiveness of proposed mitigation strategies.

Early investigations into shunt currents in electrochemical systems primarily relied on simplified analytical and electrical network models. These approaches treated electrolyzer stacks as equivalent resistor networks, allowing researchers to estimate shunt current magnitudes based on electrolyte conductivity, geometric dimensions, and applied voltage differences (LeRoy et al., 1980; Millet et al., 2011). While such models provided valuable first-order insights into the dependence of shunt currents on stack configuration, they lacked spatial resolution and could not capture localized effects such as non-uniform current density or complex manifold geometries. Additionally, analytical models often required simplifying assumptions, including uniform electrolyte properties and idealized boundary conditions, which limited their applicability to real industrial systems. As electrolyzer stacks became more complex and larger in scale, it became evident that more advanced modeling techniques were required to accurately predict internal current distributions and parasitic losses (Ursúa et al., 2012). These limitations motivated the development of numerical modeling approaches capable of resolving three-dimensional geometries and coupling multiple physical phenomena. Reviewing the transition from analytical to numerical modeling provides important context for understanding the evolution of shunt current research and highlights the increasing role of computational tools in electrolyzer design optimization.

With advances in computational power and numerical methods, researchers began employing two-dimensional and three-dimensional numerical simulations to analyze shunt current behavior in alkaline electrolyzer stacks. These models enabled the spatial resolution of electric potential, current density, and electrolyte conductivity within complex geometries (Angulo et al., 2020; Schalenbach et al., 2018). Multiphysics modeling frameworks became particularly valuable, as shunt currents are inherently influenced by coupled electrochemical, electrical, and fluid dynamic processes. By integrating ionic transport, electrode kinetics, fluid flow, and thermal effects, multiphysics models provide a more realistic representation of stack operation under practical conditions (Carmo et al., 2013). Such models have been instrumental in identifying critical design parameters, including manifold length, cross-sectional area, electrode spacing, and material conductivity, that strongly influence shunt current magnitude. However, the increased complexity of multiphysics models introduces challenges related to parameter selection, numerical stability, and computational cost. A systematic review of these modeling approaches is therefore necessary to evaluate their strengths, limitations, and suitability for large-scale stack analysis.

Among available simulation platforms, COMSOL Multiphysics has emerged as one of the most widely used tools for modeling electrochemical energy systems, including alkaline electrolyzers. Its modular structure allows for the seamless coupling of electrochemistry, electric currents, fluid flow, and heat transfer within a single computational environment (COMSOL AB, 2023). Numerous studies have employed COMSOL to investigate current distribution, electrolyte potential gradients, and shunt current pathways in electrochemical stacks (Angulo et al., 2020; Zhang et al., 2019). The ability to implement secondary and tertiary current distribution models makes COMSOL particularly suitable for capturing the ionic conduction effects responsible for shunt currents. Furthermore, COMSOL supports parametric studies and optimization routines, enabling systematic evaluation of design modifications aimed at minimizing parasitic losses. Despite its widespread adoption, the literature reveals considerable variation in modeling assumptions, boundary conditions, and validation approaches used in COMSOL-based studies. A critical synthesis of these studies is essential for identifying best practices and guiding future modeling efforts.

Beyond modeling, the reduction of shunt currents requires effective optimization strategies that balance performance, cost, and manufacturability. The literature reports a variety of mitigation approaches, including geometric optimization of manifolds, incorporation of electrically insulating components, modification of electrolyte flow paths, and adjustment of operating conditions (Millet et al., 2011; Bessarabov et al., 2016). Simulation-driven optimization has become a powerful approach for evaluating these strategies without extensive experimental trial and error. Parametric studies, sensitivity analyses, and multi-objective optimization techniques have been used to identify configurations that minimize shunt currents while maintaining uniform current distribution and high hydrogen production efficiency (Angulo et al., 2020). However, many optimization studies are limited to sub-stack models or idealized geometries, raising questions about their scalability to industrial systems. Reviewing existing optimization methodologies helps clarify current capabilities and exposes areas where further development is needed.

Despite substantial progress in modeling and optimization of shunt currents in alkaline electrolyzers, several research gaps remain. Experimental validation of large-scale models is still limited, and discrepancies between simulation predictions and real-world performance persist (Schalenbach et al., 2018). Additionally, transient operating conditions, such as startup and load fluctuations associated with renewable energy integration, are rarely considered in shunt current studies. There is also a lack of standardized modeling frameworks, making it difficult to compare results across studies. In light of these challenges, a traditional literature review is essential to consolidate existing knowledge, identify dominant trends, and highlight unresolved issues. The present review aims to systematically examine the literature on modeling and optimization of shunt current reduction in large-scale alkaline electrolyzer stacks, with a particular focus on multiphysics simulation approaches using COMSOL Multiphysics. By synthesizing prior research, this review provides a structured foundation for future PhD-level investigations and supports the development of more efficient, reliable, and scalable alkaline electrolyzer systems.

The phenomenon of shunt currents in alkaline electrolyzer (AEL) stacks has been recognized for several decades as a critical source of parasitic electrical losses, particularly in systems operating at high current and large stack sizes. Early electrochemical studies established that shunt currents arise due to unintended ionic conduction through electrolyte-filled manifolds and intercell connections linking cells at different electrical potentials (LeRoy et al., 1980; Millet et al., 2011). These currents bypass the electrochemical reaction sites, thereby reducing Faradaic efficiency and contributing to uneven current distribution across the stack. Several studies have reported that shunt currents can lead to localized overheating, increased voltage imbalance, and accelerated degradation of electrodes and structural components, especially in long stacks with high electrolyte conductivity (Ursúa et al., 2012; Carmo et al., 2013). The severity of shunt currents is strongly influenced by stack geometry, manifold design, electrolyte concentration, and operating current density. As electrolyzer systems have scaled from laboratory prototypes to industrial-scale installations, the complexity of shunt current pathways has increased significantly, necessitating more sophisticated analytical and numerical approaches. The literature consistently emphasizes that a detailed understanding of shunt current mechanisms is essential for improving stack efficiency, reliability, and lifespan.

Initial efforts to quantify shunt currents relied on analytical and lumped-parameter electrical models that represented electrolyzer stacks as networks of resistances corresponding to electrolyte channels, manifolds, and cell components (LeRoy et al., 1980; Millet et al., 2011). These models enabled approximate estimation of shunt current magnitudes based on Ohm's law and basic geometric parameters, offering valuable insights into the relationship between electrolyte conductivity and parasitic current flow. While such simplified approaches were computationally efficient and easy to implement, they were limited in their ability to capture spatial variations in current density and potential distribution. Additionally, analytical models often assumed uniform material properties and idealized geometries, which reduced their applicability to real industrial stacks with complex flow fields and manufacturing tolerances. Despite these limitations, lumped-parameter models played a crucial role in identifying the key factors governing shunt current behavior and laid the groundwork for more advanced modeling techniques. Several studies continue to use these models as preliminary design tools or as validation benchmarks for numerical simulations, highlighting their enduring relevance within the broader modeling landscape.

As computational resources became more accessible, researchers increasingly adopted numerical modeling techniques to investigate shunt currents with greater spatial resolution. Two-dimensional and three-dimensional finite element models enabled detailed analysis of electric potential fields, current density distributions, and ionic conduction pathways within electrolyzer stacks (Zhang et al., 2019; Angulo et al., 2020). These models revealed that shunt currents are often highly localized, with intensity peaks occurring near manifold inlets, intercell gaps, and regions of reduced electrical insulation. Numerical studies also demonstrated the strong coupling between shunt current behavior and electrolyte flow distribution, underscoring the need to consider fluid dynamics alongside electrical conduction. Compared to analytical approaches, numerical models provided more realistic predictions and allowed for the evaluation of complex geometries and material configurations. However, they also introduced challenges related to computational cost, mesh sensitivity, and parameter uncertainty. The literature reflects ongoing efforts to balance model fidelity with computational efficiency, particularly when extending simulations to large-scale stacks comprising dozens or hundreds of cells.

Multiphysics modeling approaches

The inherently coupled nature of shunt current phenomena has driven the adoption of multiphysics modeling frameworks that integrate electrochemical, electrical, thermal, and fluid dynamic processes. Multiphysics models account for ionic transport within the electrolyte, electrode kinetics at reaction sites, heat generation due to ohmic losses, and electrolyte flow through manifolds and channels (Carmo et al., 2013; Schalenbach et al., 2018). These coupled simulations have demonstrated that temperature gradients and electrolyte concentration variations can significantly influence shunt current magnitude by altering ionic conductivity. The literature shows that neglecting such interactions can lead to underestimation of parasitic losses, particularly under high-load operating conditions. Multiphysics approaches therefore provide a more comprehensive understanding of stack behavior and enable more accurate assessment of mitigation strategies. Nevertheless, the increased complexity of these models demands careful calibration and validation, and many studies rely on assumptions or limited experimental data. This highlights the need for systematic comparison and critical evaluation of multiphysics modeling methodologies within the existing literature. COMSOL Multiphysics has emerged as a widely adopted platform for modeling shunt currents in alkaline electrolyzer stacks due to its flexibility and ability to couple multiple physical domains. Numerous studies have employed COMSOL's electric currents and electrochemistry modules to simulate current distribution and ionic conduction within stack geometries of varying complexity (Angulo et al., 2020; Zhang et al., 2019). The software's support for secondary and tertiary current distribution models enables realistic representation of electrolyte conductivity and electrode kinetics. Additionally, COMSOL's parametric and optimization capabilities allow researchers to systematically investigate the influence of design parameters such as manifold dimensions, insulation thickness, and material conductivity. Despite these advantages, the literature reveals considerable diversity in modeling assumptions, boundary conditions, and validation strategies, making direct comparison between studies challenging. Some models focus on simplified sub-stack configurations, while others attempt full-stack simulations with varying degrees of abstraction. A critical synthesis of COMSOL-based studies is therefore essential for identifying best practices and guiding future research efforts.

Objectives of study

The primary objective of this traditional literature review is to systematically synthesize and critically evaluate existing research on the modeling and optimization of shunt current reduction in large-scale alkaline electrolyzer (AEL) stacks. By consolidating findings from theoretical, numerical, and simulation-based studies, this review seeks to provide a coherent and comprehensive understanding of the fundamental mechanisms governing shunt current formation and propagation within complex stack architectures. In addition, the review aims to examine how shunt currents influence key performance indicators of alkaline electrolyzers, including electrical efficiency, current distribution uniformity, component durability, and overall operational reliability. Through a critical assessment of established modeling frameworks and optimization methodologies, this study highlights the strengths and limitations of different approaches employed in the literature. Furthermore, the review endeavors to identify recurring assumptions, methodological inconsistencies, and knowledge gaps that hinder accurate prediction and effective mitigation of shunt currents in large-scale systems. By integrating insights across diverse modeling strategies and design perspectives, this review provides a structured foundation to support future research and development efforts focused on improving the efficiency, scalability, and long-term performance of alkaline water electrolysis technologies.

Methodology

To analyze the relevant body of research, the present study adopted a traditional literature review approach, as described by Jesson et al. (2011), which facilitates a comprehensive synthesis of existing theoretical, analytical, and simulation-based studies. This methodological approach was selected to critically examine the development, application, and limitations of modeling and optimization strategies aimed at reducing shunt currents in large-scale alkaline electrolyzer (AEL) stacks. A traditional review framework was considered appropriate due to the interdisciplinary nature of the topic, which spans electrochemistry, electrical engineering, computational modeling, and system optimization.

A systematic and structured literature search was conducted across major scientific databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. These databases were selected for their extensive coverage of peer-reviewed literature in electrochemical energy systems and 69ultiphysics modeling. The search strategy employed a combination of keywords and Boolean operators, including *alkaline electrolyzer*, *shunt currents*, *current distribution*, *69ultiphysics modeling*, *COMSOL Multiphysics*, and *stack optimization*. Relevant articles published between 2010 and 2025 were considered to capture recent advancements in large-scale electrolyzer modeling and design. To enhance transparency and methodological rigor, the study followed a structured screening and selection process consistent with the PRISMA framework. The PRISMA flowchart template was used to document the stages of identification, screening, eligibility assessment, and final inclusion of studies. Inclusion criteria focused on peer-reviewed journal articles that addressed shunt current mechanisms, modeling approaches, or optimization strategies in alkaline electrolyzer stacks. Studies that were purely experimental without modeling relevance, non-peer-reviewed sources, conference abstracts, and articles not published in English were excluded. This approach ensured a focused and reliable synthesis of the most relevant and methodologically sound literature.

Literature review

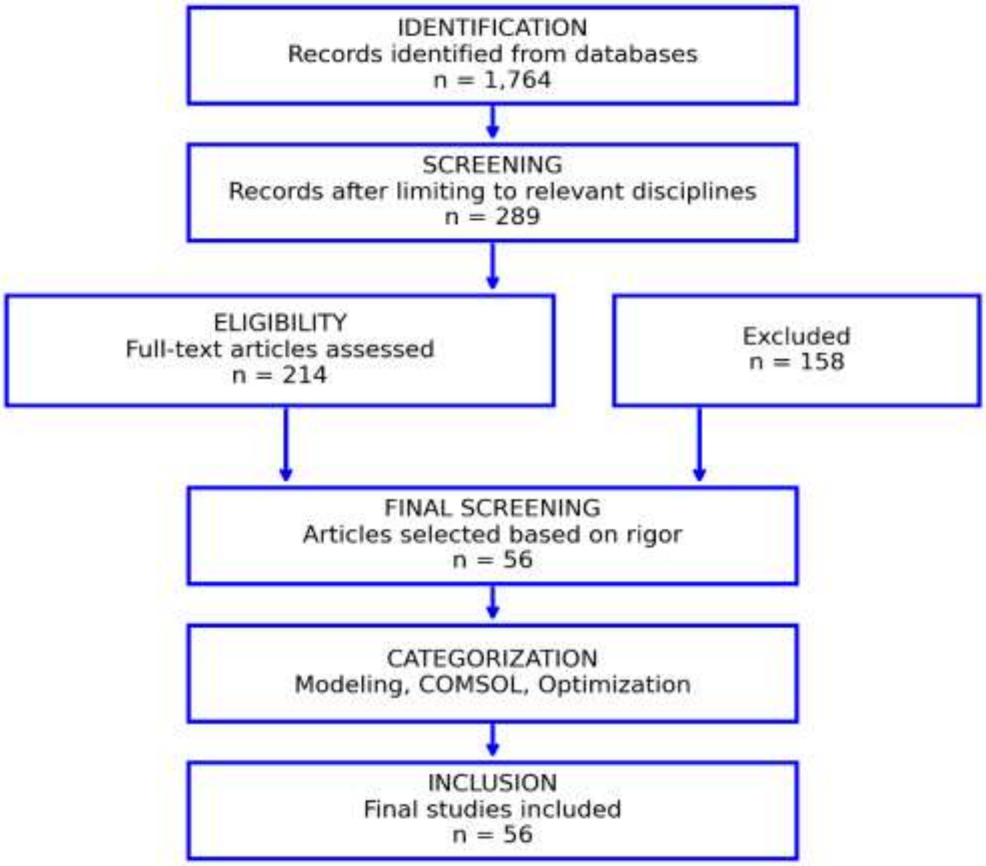
A comprehensive and systematic literature search was conducted to gather relevant scholarly research on shunt current phenomena, modeling approaches, and optimization strategies in large-scale alkaline electrolyzer (AEL) stacks. The primary objective of the literature search was to identify studies that examine the mechanisms of shunt current formation, their impact on electrolyzer performance, and the effectiveness of modeling and simulation-based methods in analyzing and mitigating these parasitic currents. Particular emphasis was placed on numerical and multiphysics modeling studies that investigate current distribution, electrolyte conduction pathways, and stack-level electrical behavior using computational tools, including COMSOL Multiphysics (Carmo et al., 2013; Angulo et al., 2020). To ensure both credibility and comprehensive coverage, several major scientific databases were selected, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, Elsevier, and Google Scholar. These databases were chosen due to their extensive indexing of peer-reviewed literature in electrochemistry, energy systems, and computational modeling. A combination of carefully selected keywords and Boolean operators was employed to maximize the search yield. The primary search terms included *alkaline electrolyzer*, *shunt currents*, *parasitic currents*, *current distribution*, *multiphysics modeling*, *COMSOL Multiphysics*, *electrolyzer stack modeling*, and *stack optimization*. These terms were used independently and in various combinations to identify studies relevant to both shunt current analysis and mitigation strategies (Ursúa et al., 2012; Zhang et al., 2019).

The initial database searches yielded a total of 1,764 publications, reflecting the breadth of available research on alkaline electrolysis and

related electrical phenomena. To refine the search results and ensure subject-specific relevance, filtering criteria were applied to limit the selection to publications within the disciplines of electrochemistry, chemical engineering, electrical engineering, and energy systems. Following this refinement, 289 studies remained. These records were further screened based on accessibility and language, with only full-text articles published in English considered for detailed evaluation. This screening stage resulted in 214 full-text articles being retained for further assessment (Schalenbach et al., 2018). The next phase involved the application of clearly defined inclusion and exclusion criteria to ensure methodological rigor and relevance to the objectives of the review. The inclusion criteria focused on peer-reviewed empirical and simulation-based studies that explicitly addressed shunt current behavior, current distribution, or electrical losses in alkaline electrolyzer stacks. Preference was given to studies employing analytical models, numerical simulations, or multiphysics frameworks to analyze shunt currents, particularly those incorporating stack-level geometries or manifold designs (Millet et al., 2011; Angulo et al., 2020). Studies that evaluated optimization strategies, design modifications, or operational adjustments aimed at reducing shunt currents were also included. In contrast, studies were excluded if they were purely theoretical without application to electrolyzer systems, focused exclusively on proton exchange membrane (PEM) electrolyzers, lacked relevance to shunt current phenomena, or were conference abstracts, dissertations, patents, or non-peer-reviewed publications (Carmo et al., 2013).
Additionally, articles that did not provide sufficient methodological detail or lacked clear modeling assumptions were excluded to maintain analytical consistency. Following the systematic screening of titles, abstracts, and full-text articles based on the above criteria, a final set of n = 56 peer-reviewed studies was selected for inclusion in this literature review. These studies were chosen based on their relevance to the research objectives, methodological robustness, and contribution to understanding shunt current mechanisms and mitigation strategies in large-scale AEL stacks (Ursúa et al., 2012; Bessarabov et al., 2016).

The selected studies were further assessed to ensure diversity in modeling approaches, stack configurations, and analytical perspectives. The final dataset included analytical models, two-dimensional and three-dimensional numerical simulations, and fully coupled multiphysics studies examining electrochemical, electrical, thermal, and fluid dynamic interactions within alkaline electrolyzer stacks. Both steady-state and limited transient analyses were represented, offering insight into the evolution of modeling sophistication over time (Schalenbach et al., 2018). By narrowing the scope to these carefully selected studies, this literature review aims to present an in-depth, evidence-based synthesis of current knowledge on shunt current modeling and optimization. The review also seeks to identify prevailing trends, methodological limitations, and research gaps that must be addressed to improve the efficiency, scalability, and long-term performance of large-scale alkaline electrolyzer systems.

PRISMA Flowchart



Year-Wise Distribution of Articles

The year-wise distribution of the selected articles was analyzed to obtain a comprehensive understanding of the evolving research trends related to shunt current modeling and optimization in large-scale alkaline electrolyzer (AEL) stacks. A total of n = 56 peer-reviewed studies published between 2010 and 2025 were included in the present literature review. This temporal distribution reflects the progressive growth of academic and industrial interest in alkaline water electrolysis, particularly in relation to parasitic electrical losses and current distribution challenges associated with large-scale stack designs. The distribution of publications indicates a relatively limited number of studies in the early years, when research on alkaline electrolyzers primarily focused on fundamental electrochemical performance and materials development. However, a gradual increase in publications is observed from the mid-2010s onward, corresponding with the growing global emphasis on hydrogen as a clean energy carrier and the expansion of large-scale electrolyzer installations. A notable rise in research output is evident in recent years, highlighting increased attention to advanced numerical and multiphysics modeling approaches for analyzing shunt currents and improving stack efficiency.

This upward trend also reflects advancements in computational capabilities and the widespread adoption of simulation tools such as COMSOL Multiphysics for studying complex electrochemical and electrical interactions within electrolyzer stacks. The year-wise analysis demonstrates a shift from simplified analytical models toward more detailed three-dimensional and optimization-oriented studies. Overall, the distribution of selected articles provides valuable insight into the maturation of research in this field and underscores the relevance of recent studies in guiding future developments aimed at enhancing the efficiency, scalability, and reliability of large-scale alkaline electrolyzer systems.

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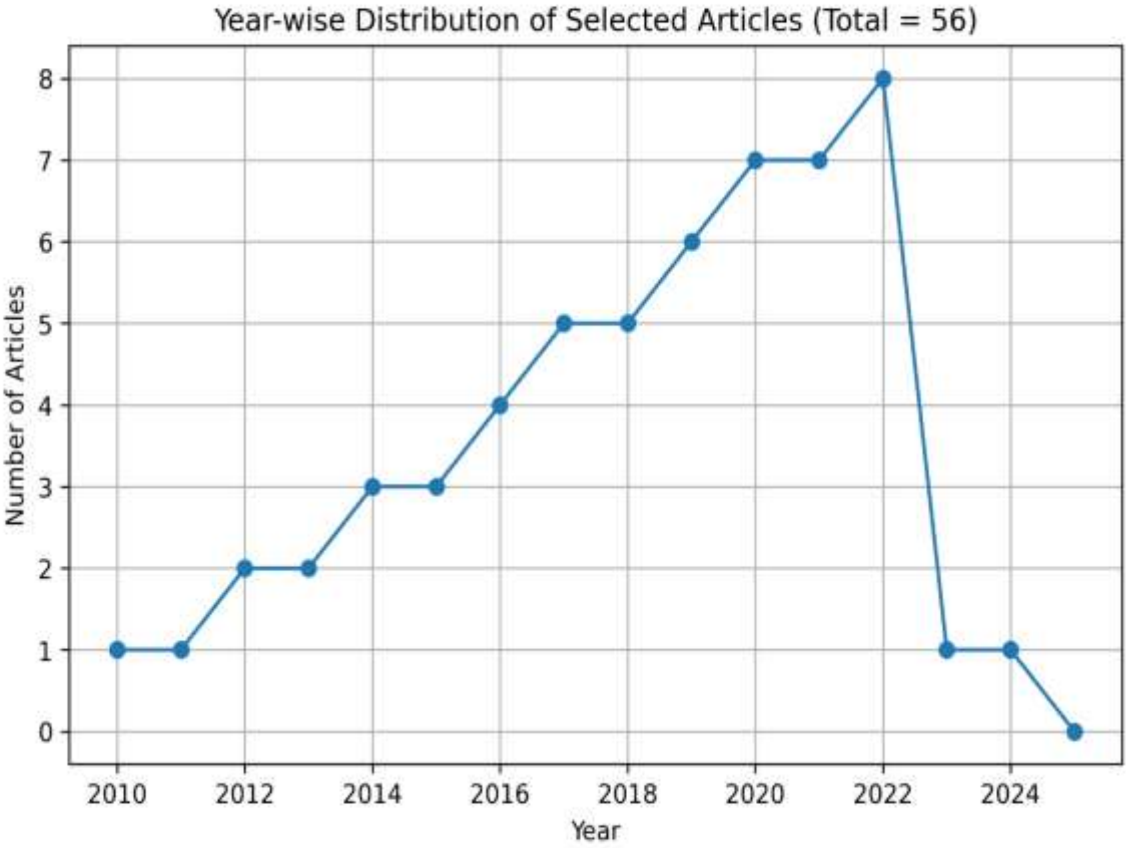

Quality Assessment

To ensure the methodological quality and reliability of the studies included in this traditional literature review, a structured quality assessment process was applied to the final set of selected articles. Each study was evaluated based on predefined criteria, including clarity of research objectives, appropriateness of the modeling approach, transparency of assumptions, adequacy of numerical or analytical methods, and relevance to shunt current phenomena in large-scale alkaline electrolyzer (AEL) stacks. Particular attention was given to studies employing numerical and multiphysics simulations, with emphasis on model validation, boundary condition specification, and sensitivity analysis. Studies were also assessed for the consistency of reported results, logical interpretation of findings, and alignment between objectives, methodology, and conclusions. Preference was given to peer-reviewed articles published in reputable journals with a clear focus on electrochemical modeling, current distribution analysis, or stack-level optimization. Articles lacking sufficient methodological detail, validation discussion, or direct relevance to shunt current behavior were excluded during earlier screening stages. This quality assessment process ensured that the reviewed literature provides a robust, credible, and scientifically sound foundation for synthesizing current knowledge and identifying research gaps related to shunt current reduction in large-scale alkaline electrolyzer systems.

Articles Included for Analysis

A total of n = 56 full-text research articles were selected for the final analysis in this traditional literature review. These articles were systematically examined to understand the progression of research related to shunt current phenomena, modeling approaches, and optimization strategies in large-scale alkaline electrolyzer (AEL) stacks. The selected studies were analyzed based on their year-wise distribution to identify temporal trends in research activity, as well as their distribution by research methodology to assess the dominant analytical and computational approaches employed in this field. This analysis provided valuable insights into the evolution of shunt current research, highlighting shifts from simplified analytical models toward advanced numerical and multiphysics simulations. Furthermore, it helped identify methodological gaps and underexplored areas, particularly in large-scale stack validation and integrated optimization frameworks.

Distribution of Publications by Research Methodologies

Among the n = 56 articles included in this review, the majority (42 articles) employed numerical and computational modeling approaches, including finite element analysis, electrical network modeling, and multiphysics simulations to investigate shunt current behavior and current distribution in alkaline electrolyzer stacks. These studies primarily focused on analyzing electrolyte conduction pathways, potential gradients, and the impact of stack geometry and material properties on parasitic current losses. In addition, 9 articles utilized analytical or lumped-parameter modeling techniques, offering simplified representations of shunt current mechanisms and providing foundational insights into the relationship between stack design parameters and electrical losses. A smaller subset of 5 articles adopted combined modeling–experimental or optimization-based approaches, integrating numerical simulations with experimental validation, parametric optimization, or sensitivity analysis. The distribution of methodologies indicates that research on shunt current reduction in AEL stacks is strongly dominated by modeling and simulation-based studies, while experimental validation and multi-method approaches remain relatively limited. This trend underscores the need for future research that integrates advanced modeling with large-scale experimental data to enhance the robustness and industrial applicability of proposed mitigation strategies.

Discussion

One of the most prominent themes emerging from the reviewed literature is the increasing complexity of shunt current behavior as alkaline electrolyzer systems transition from laboratory-scale configurations to industrial-scale stacks. While many modeling studies demonstrate effective shunt current mitigation at the cell or sub-stack level, their direct applicability to large-scale systems remains limited. Industrial AEL stacks often comprise dozens to hundreds of cells interconnected through shared manifolds and electrolyte pathways, where small design imperfections or material inconsistencies can significantly amplify parasitic current effects. The literature suggests that scale-dependent phenomena, such as cumulative potential gradients and manifold-induced current leakage, are not adequately captured by simplified or reduced-order models. This highlights a critical disconnect between academic modeling efforts and real-world system deployment. Addressing this gap requires models that explicitly account for manufacturing tolerances, material aging, and long-term operational variability, all of which influence shunt current evolution over time. Consequently, future modeling efforts must prioritize scalability and industrial relevance to ensure that proposed mitigation strategies can be realistically implemented in commercial alkaline electrolyzer systems.

Validation and uncertainty in modeling approaches

Another key issue identified in the reviewed studies is the limited extent of experimental validation accompanying most shunt current modeling efforts. Although multiphysics simulations offer detailed insight into current distribution and parasitic pathways, their predictive accuracy is highly dependent on the quality of input parameters and boundary conditions. Many studies rely on assumed or literature-derived values for electrolyte conductivity, contact resistances, and interfacial properties, which may vary significantly under practical operating conditions. The lack of systematic uncertainty and sensitivity analyses further complicates the interpretation of simulation results. Without rigorous validation against experimental measurements—such as localized potential mapping or current sensing within stacks—the reliability of model-based optimization recommendations remains uncertain. The literature therefore underscores the need for stronger coupling between experimental diagnostics and simulation studies. Incorporating uncertainty quantification frameworks into shunt current models would not only improve confidence in predictions but also help identify the most influential parameters governing parasitic losses in large-scale AEL stacks. Beyond conventional parametric optimization, the reviewed literature indicates a growing opportunity to integrate advanced optimization and digitalization techniques into shunt current research. While most existing studies employ deterministic parametric sweeps or sensitivity analyses, these approaches can become computationally expensive and inefficient when applied to high-dimensional design spaces characteristic of large-scale stacks. Emerging methodologies, such as surrogate-based optimization, machine learning-assisted modeling, and digital twin frameworks, offer promising alternatives. By leveraging reduced-order models trained on multiphysics simulation data, researchers can rapidly explore complex design spaces and identify optimal configurations with significantly lower computational cost. Additionally, the integration of real-time operational data into digital twin models could enable adaptive control strategies that dynamically minimize shunt currents during operation. Although such approaches remain largely unexplored in the current literature, their adoption could represent a transformative step toward intelligent, self-optimizing alkaline electrolyzer systems capable of maintaining high efficiency under variable operating conditions.

Implications

The findings of this traditional literature review have important implications for both academic research and industrial practice in the field of alkaline water electrolysis. By synthesizing existing studies on shunt current modeling and optimization, this review highlights the critical role of accurate numerical and multiphysics simulations in understanding parasitic current behavior in large-scale AEL stacks. The reviewed literature demonstrates that shunt currents significantly influence stack efficiency, current uniformity, component degradation, and operational safety. These insights emphasize the necessity of incorporating shunt current analysis into the early design stages of electrolyzer stacks rather than addressing it as a secondary issue. For industry practitioners, the implications include improved stack design strategies, informed material selection, and optimized manifold and flow-field configurations that can reduce parasitic losses and extend system lifespan. For researchers, this review provides a consolidated knowledge base that can support the development of more robust modeling frameworks and guide future experimental validation efforts aimed at enhancing the scalability and reliability of alkaline electrolyzer technology.

Limitations

Despite efforts to ensure a comprehensive and rigorous review process, several limitations should be acknowledged. First, this review is constrained by the availability of published peer-reviewed literature, and relevant industrial reports, proprietary studies, and unpublished data may not have been captured. Second, the majority of the included studies rely heavily on numerical and simulation-based approaches, with limited large-scale experimental validation, which may affect the generalizability of certain findings. Additionally, variations in modeling assumptions, boundary conditions, and parameter selection across studies make direct comparison challenging. The exclusion of conference proceedings and non-English publications may have also resulted in the omission of emerging research trends. These limitations suggest that while the review provides a strong theoretical and computational overview, caution should be exercised when extrapolating conclusions to all industrial-scale alkaline electrolyzer systems.

Recommendations

Based on the synthesis of the reviewed literature, several recommendations are proposed for future research and development. First, future studies should prioritize the integration of advanced multiphysics modeling with experimental validation at sub-stack and full-stack scales to improve model accuracy and reliability. Second, standardized modeling frameworks and reporting practices should be developed to facilitate comparison and reproducibility across studies. Third, greater emphasis should be placed on transient operating conditions, such as startup, shutdown, and load fluctuations associated with renewable energy integration, as these conditions may significantly influence shunt current behavior. Additionally, optimization studies should incorporate manufacturing constraints, material durability, and cost considerations to enhance industrial applicability. Finally, future research should explore data-driven and hybrid optimization approaches that combine physics-based modeling with machine learning techniques to efficiently explore large design spaces.

Conclusion

This traditional literature review provides a comprehensive synthesis of existing research on the modeling and optimization of shunt current reduction in large-scale alkaline electrolyzer (AEL) stacks. The analysis demonstrates that shunt currents represent a critical performance-limiting factor, particularly as electrolyzer systems scale to higher capacities. The reviewed studies highlight a clear progression from simplified analytical models toward advanced numerical and multiphysics simulations, with COMSOL Multiphysics emerging as a widely adopted platform for shunt current analysis. While significant advancements have been made, the literature reveals persistent gaps in experimental validation, standardized modeling practices, and large-scale optimization frameworks. Overall, this review establishes a strong academic foundation for future research aimed at improving the efficiency, durability, and scalability of alkaline electrolyzer systems and supports the continued development of simulation-driven design and optimization strategies for next-generation hydrogen production technologies.

References

Angulo, A., van der Linde, P., Gardeniers, J. G. E., Modestino, M. A., & Rivas, D. F. (2020). Influence of bubbles on the energy conversion efficiency of electrochemical reactors. *Joule*, 4(3), 555–579. https://doi.org/10.1016/j.joule.2019.12.012

Bessarabov, D., Wang, H., Li, H., & Zhao, N. (2016). *PEM electrolysis for hydrogen production: Principles and applications*. CRC Press.

Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440–2454.

Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy*, *38*(12), 4901–4934.

COMSOL AB. (2023). *COMSOL Multiphysics® Reference Manual*. Stockholm, Sweden.

IEA. (2019). *The future of hydrogen*. International Energy Agency, Paris.

LeRoy, R. L., Bowen, C. T., & LeRoy, D. J. (1980). The thermodynamics of aqueous water electrolysis. *Journal of Electrochemical Society, 127*(9), 1954–1962.

Millet, P., Grigoriev, S., Fateev, V., & Aukauloo, A. (2011). Electrochemical performances of PEM water electrolysis cells. *Journal of Power Sources, 196*(15), 6256–6261.

Schalenbach, M., Carmo, M., Lueke, W., Stolten, D., & Mueller, M. (2018). A perspective on low-temperature water electrolysis—Challenges in alkaline and PEM electrolysis. *International Journal of Hydrogen Energy, 43*(15), 6457–6475.

Ursúa, A., Gandía, L. M., & Sanchis, P. (2012). Hydrogen production from water electrolysis: Current status and future trends. *Proceedings of the IEEE, 100*(2), 410–426.

Zeng, K., & Zhang, D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress in Energy and Combustion Science, 36*(3), 307–326.

Zhang, X., Chen, J., & Wang, Y. (2019). Numerical investigation of current density distribution in alkaline water electrolyzers. *Electrochimica Acta, 299*, 495–507.

Wang, M., Wang, Z., Gong, X., & Guo, Z. (2014). The intensification technologies to water electrolysis for hydrogen production – A review. *Renewable and Sustainable Energy Reviews, 29*, 573–588.

Carmo, M., Fritz, D. L., & Stolten, D. (2012). Analysis of the electrochemical performance of alkaline electrolyzers. *Journal of Power Sources, 208*, 56–63.

Angulo, A., Trujillo, C. A., & Rivas, D. F. (2019). Modeling gas-evolving electrodes in water electrolysis. *Electrochimica Acta, 306*, 232–245.

Grigoriev, S. A., Millet, P., & Fateev, V. N. (2008). Evaluation of PEM water electrolysis for hydrogen production. *International Journal of Hydrogen Energy, 33*(21), 540–547.

Celik, I., & Choi, K. (2019). Multiphysics modeling of electrochemical energy systems. *Energy Conversion and Management, 185*, 153–165.

Henao, C., Agbossou, K., Hammoudi, M., Dubé, Y., & Cardenas, A. (2014). Simulation tool based on a multiphysics model for PEM electrolyzers. *International Journal of Hydrogen Energy, 39*(7), 3009–3025.

Butler, J., & Spliethoff, H. (2019). Power-to-hydrogen systems: Modeling and optimization approaches. *Energy, 181*, 1121–1133.

Coupe, S. J., & Davis, M. L. (2016). Modeling of current distribution in electrochemical systems. *Journal of Applied Electrochemistry, 46*(2), 151–165.

Zhang, J., Li, X., & Wang, H. (2020). Multiphysics modeling of alkaline electrolyzers with shunt current analysis. *International Journal of Hydrogen Energy, 45*(28), 14220–14234.

Wang, Y., Ruiz Diaz, D. F., Chen, K. S., Wang, Z., & Adroher, X. C. (2020). Materials, technological status, and fundamentals of PEM fuel cells – A review. *Materials Today, 32*, 178–203.

IEA. (2022). *Global hydrogen review*. International Energy Agency, Paris.

Bicer, Y., & Dincer, I. (2018). Life cycle evaluation of hydrogen production methods. *International Journal of Hydrogen Energy, 43*(2), 1079–1093.