iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VI **Month of publication:** June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72642

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Advancing Green Hydrogen: Enhancing Electrolysis Efficiency for Sustainable Energy Transition

Dhruvendra Kumar Chourishi[1], Hitendra Singh Tomar[2], Pratap Singh Katara[3]
[1]Department of Computer Science Government Polytechnic College Agar Malwa M.P
[2]Department of Chemistry GovernmentPolytechnicCollege Agar Malwa M.P
[3]Department of Electronics GovernmentPolytechnicCollege Agar Malwa M.P

Abstract: Green hydrogen, produced via water electrolysis poweredbyrenewableenergy,isakeysolutionfordecarbonizing various industries. However, its widespread adoption is hindered by high energy consumption and production costs. Enhancing electrolysis efficiency is crucial to making green hydrogen eco- nomically viable and sustainable. This paper explores advance- ments in electrolyzer technologies, including Proton Exchange Membrane (PEM), Alkaline, and Solid Oxide Electrolysis Cells (SOEC),withafocusonimprovingcatalystmaterials,reduc- ing overpotentials, and increasing operational flexibility. The development of cost effective, high-performance catalysts suchas nanostructured non-precious metals enhances reaction kinet- ics and stability. Furthermore, integrating artificial intelligence (AI)forreal-timeoptimizationandsmartgridmanagement can improve efficiency by dynamically adjusting to fluctuating renewable energy inputs. Additionally, hybrid systems that com- bine electrolysis with heat recovery and advanced membrane technologies can further enhance performance. By addressing these technological and operational challenges, green hydrogen productioncanbecomemoreefficient,cost-effective,andscalable, accelerating the transition to a clean energy future.

Index Terms: Green hydrogen, Electrolysis, PEM, SOEC, Catalyst, Renewable energy, Artificial Intelligence, Smart grid.

I. INTRODUCTION

Electrolysis,theprocessofsplittingwaterintohydrogenandoxygenusingelectricity,requiressubstantialenergyinput.Theefficiencyofthisprocessdependsonseveralfactors,includingthetypeofelectrolyzerused,catalystmaterials,membraneperformance,andintegrationwithrenewableenergysources.Currently,threemainelectrolyzertechnologiesareused:ProtonExchangeMembrane(PEM)Electrolyzers,AlkalineElectrolyzers,andSolidOxideElectrolysisCells(SOECs),eachwithitsadvantagesandlimitations[1].Advancementsincatalystdesign,membraneconductivity,andsystemoptimizationarecrucialtoimprovingperformanceandmakinggreenhydrogenmorecompetitivewithfossilfuels[6].Furthermore,integratingelectrolysiswithartificialintelli-gence(AI)-drivencontrolsystems,wasteheatrecovery,and smartgridtechnologiescanenhanceefficiencyandreduce operationalcosts.Byaddressingthesechallenges,greenhy- drogen can play a pivotal role in the global transition towards sustainableenergy.Thisstudyfocusesonstrategiestoen- hancetheefficiency ofelectrolysis, exploringtechnological innovations,materialadvancements,andsystemoptimizationtechniques that can contribute to a more viable and cost- effectivehydrogeneconomy[7].Greenhydrogen,producedvia water electrolysis powered by renewable energy sources such as solar and wind, is increasingly recognized as a key com- ponent in achieving carbon neutrality and decarbonizing var- ious sectors, including transportation, power generation, and heavy manufacturing. Unlike traditional hydrogen production methods[4], such as steam methane reforming (SMR), which emitsignificantgreenhousegases,greenhydrogenprovides a sustainable alternative with minimal environmental impact. However, the large-scale adoption of green hydrogen faces challenges primarily related to the efficiency of electrolysis processes. The efficiency of electrolysis directly influences production costs, energy consumption, and the overall feasi- bility of green hydrogen as a viable energy source.

Proton Exchange Membrane (PEM) Electrolyzers Known fortheirhighefficiencyandrapidresponsetimes,Itissuitable fordynamicoperationbutcanbemoreexpensivedueto the use of precious metals in catalysts. Another is Alkaline Electrolyzers it is cost-effective and have a long track record but typically operate at lower efficiencies and may require largersystemsforhighproductionrates[5].WhileSolidOxide Electrolysis Cells (SOECs) Operats at high temperatures, SOECs can achieve higher efficiencies but face challenges related to material stability and operational complexity.

The Catalyst Materials significantly impacts the reaction kinetics and overall efficiency of the electrolysis process[3]. Researchintonon-preciousmetalcatalystsandnovelmaterials aims to reduce costs and improve performance. The conduc- tivity and durability of membranes used in electrolyzers are critical for efficient operation. Innovations in membrane tech- nology can enhance ion transport and reduce energy losses. Optimizing the coupling of electrolyzers with solar and wind resources can enhance operational efficiency and reliability.

Advancements in these areas are essential for improving electrolysis performance and making green hydrogen more competitive with fossil fuels. Additionally, utilizing wasteheat recovery and smart grid technologies can further reduce operational costs and increase the viability of green hydrogen production. This study focuses on strategies to enhance the efficiencyofelectrolysis,exploringtechnologicalinnovations, materialadvancements,andoptimizationtechniquesthatcan contribute to a more sustainable and economically viable hydrogen economy. By addressing these challenges, green hydrogen can play a pivotal role in the global transition towards sustainable energy solutions.

II. ANALYSING METHODS OF ENHANCING EFFECIENCY

Theefficiencyofelectrolysisforgreenhydrogenproduction is a critical area of research that can lead to more sustainable and cost-effective hydrogen generation. Here are several ap- proaches and strategies that can be concidered[10].

1) Catalysts:Investigatenewcatalyststhataremoreefficient and less expensive than traditional precious metal catalysts (like platinum). Non-precious metal catalysts, such as tran- sition metal oxides or nitrides, can be explored for their effectiveness in facilitating the electrolysis reaction. another very effective material may be membrane materials with higher ionic conductivity and durability[8]. This can reduce energy losses during ion transport and enhance overall cell performance. Different electrode designs can also improve surface area and mass transport, which can lead to higher reaction rates. Other than these the following factors can also be very effective in enhancing effeciency[9]
2) Pressure and Temperature: Research the effects of op- erating at higher pressures and temperatures on electrolysis efficiency, leading to improved performance.Higher pressure can enhance the solubility of gases in liquids, reduce bubble formation,andmayimprovetheefficiencyofcertaintypes of electrolyzers. Additionally, producing hydrogen at higher pressures can reduce the energy required for subsequent com- pressionandstorage.Hydrogenstoragesystemsaresensitiveto temperature fluctuations. High temperatures can increase the pressure within storage tanks, requiring careful managementto prevent safety hazards. Conversely, low temperatures can affect the material properties of storage tanks and the overall integrity of the system.The interplay between pressure and temperature is crucial for optimizing the entire lifecycle of green hydrogen, from production to storage and utilization. Understanding and managing these parameters can lead to improved efficiencies and reduced costs associated with green hydrogen technologies
3) Current Density Optimization: Identify optimal current densitiesfordifferentelectrolyzertypestomaximizehydrogen production while minimizing energy consumption.
4) Dynamic Operation: Develop systems that can adjust electrolysis operation based on the availability of renewable energysourceslikesolarorwind.Thiscanhelpinmaximizing efficiency during peak energy production times.
5) Energy Management Systems: Implement AI-driven en- ergy management systems that optimize the integration of electrolyzerswithrenewableenergysources,ensuringefficient operation.
6) Real-Time Monitoring: Utilize sensors and IoT tech- nologytomonitorparameterssuchastemperature,pres- sure, and gas composition in real-time, allowing for dynamic adjustmentstoimproveefficiency.Applymachinelearning algorithms to analyze operational data and predict optimal conditions for electrolysis, thereby enhancing performance.
7) Investigatethedynamicsofgasbubblesgeneratedduring electrolysis. Understanding bubble formation, growth, and detachment can provide insights into optimizing cell design and operating conditions to minimize energy losses associated with bubble formation.
8) Explore hybrid systems that combine electrolysis with other processes, such as photocatalysis or thermochemical cycles,toimproveoverallhydrogenproductionefficiencyand reduce energy input.

By focusing on these areas, researchers can contribute tothe advancement of electrolysis technology, making green hydrogen production more efficient and economically viable, ultimately supporting the transition to a sustainable energy future. Enhancing the efficiency of electrolysis for green hydrogen production is critical for reducing costs, improving sustainability, and accelerating the transition to clean energy. Other key areas of research to improve efficiency:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

- AdvancedElectrodeMaterialsweneeedthatcanproduce high-performance and cost-effective like nickel, cobalt, iron instead of platinum or iridium.Similarly Catalysts for higher surface area and reactivity. to enhance conductivity and dura- bility. by using coatings of metal oxides, conductive polymers to reduce overpotential.
- Electrolyte Optimization Improve potassium hydroxide (KOH) or sodium hydroxide (NaOH) electrolyte concentra- tion. Proton Exchange Membrane (PEM) Electrolyzers to Develop more durable, cost-effective membranes. and Solid Oxide Electrolyzers (SOEC) to high-temperature electrolytes for improving efficiency[2].
- Enhanced cell design (i)Minimize ohmic losses by op- timizingmembranethicknessandimprovingconductivity.
- (ii) Flow Field Design, Enhance gas diffusion using ad- vanced flow channels. (iii) Bipolar Plate Materials It uses lightweight,corrosion-resistantmaterials(e.g.coatedstainless steel, graphite).
- Process optimization and operational strategies dynamic Operation Adapt electrolyzers to variable renewable energy sources (solar, wind). Temperature and pressure control can reduce energy consumption in SOEC systems. Pulse Electrol- ysis Techniques to Reduce Electrode Degradation.
- To enhance the efficiency of water electrolysis for green hydrogen production, a multifaceted approach that integrates advanced materials, engineering innovations, and intelligent control systems is essential. The development of nanostruc- tured and hybrid electrode catalysts significantly boosts reac- tion kinetics while reducing the reliance on costly platinum- group metals, although challenges remain with respect tolong-term stability and large-scale production. Electrolyte op- timization plays a pivotal role in improving ionic conduc- tivity and reducing ohmic losses across various electrolyzer technologies, yet issues such as component corrosion and membranedegradation,particularlyunderhigh-temperatureor high-current conditions, persist. Improved cell designs that incorporateoptimizedflowfieldsandmodulararchitectures enhancehydrogenpurityandscalabilitybutofteninvolvehigh manufacturing costs and complex system integration. Opera- tional strategies such as pulsed electrolysis and dynamic load adjustment help align hydrogen production with fluctuating renewable energy inputs, improving energy efficiency and componentlifespan,necessitatesophisticatedreal-timecontrol systems. Direct integration with renewable sources such as solarphotovoltaicsandwindturbinesfacilitateszero-emission hydrogen generation and offers an effective energy storage solution,althoughwithintermittencyandinfrastructure-related challenges.Finally,theapplicationofAIandmachinelearning introduces transformative potential through process optimiza- tion,predictivemaintenance,anddata-drivendecisionmaking in real time, although these technologies require significant investment,robustdatainfrastructure,andstrongcybersecurity measures.Together,thesestrategiescontributetomakingelec- trolysis a more viable and sustainable pathway for large-scale greenhydrogenproduction.Althougheachresearchareaoffers uniqueadvantagesandchallenges.Thebestapproachdepends on the balance between efficiency, cost, and scalability.

TableI
COMPARISONOFELECTROLYZERTECHNOLOGIES

Parameter	Alkaline	PEM	SOEC
Temp (°C)	60–90	50–80	600–850
Electrolyte	KOHSol.	SolidPolymer	SolidOxide
Catalyst	Ni,Fe	Pt,Ir,non-prec.	Ni-YSZ,perov.
Efficiency	∼60–70%	∼65–75%	∼80–90%
CapEx	Low	Med–High	High
Startup	Min	Sec–Min	Hours
AIUse	Moderate	High	High
R&DFocus	Costred.	Cat.innov.	Durab.,mat.

III. METHODS USING MACHINE LEARNING

MachineLearning(ML)cansignificantlyimprovehydrogen electrolysis by optimizing processes, predicting failures, and reducing energy consumption. The integration of machine learning (ML) into water electrolysis systems offers a trans- formativepathwaytowardenhancingefficiencyandsupporting the global shift to sustainable energy.

This algorithms enable real-timeoptimizationofoperatingparameterssuchasvoltage, currentdensity,temperature, andpressure, allowingelectrolyz- ers to adapt dynamically to fluctuating renewable energy inputs. This adaptability ensures more consistent hydrogen production and minimizes energy losses under variable con- ditions.

Predictive maintenance models, trained on historical and real-time sensor data, can detect faults and anticipate componentdegradation,therebyreducingunplanneddowntime andextendingsystemlifespan.Furthermore,thisfacilitatesthe analysis of complex datasets to identify performance trends, optimizecontrolstrategies,andimproveoverallsystemdesign. When combined with other innovations such as advanced materials and optimized cell architecture ML enhances the ability to operate electrolyzers efficiently at scale and under intermittent renewable energy conditions. This synergy not only improves hydrogen yield and lowers operational costsbutalsoacceleratestheintegrationofgreenhydrogenintothe energy mix, making it a key enabler of the sustainable energy transition.

Machine learning is revolutionizing the design and opti- mization of electrolysis components by accelerating material discovery, enhancing system durability, and reducing energy losses. In the development of advanced electrode materials,it enables rapid prediction of catalyst performance by virtually modeling electrochemical behavior, thereby reducing reliance oncostlyandtime-consumingexperimentaltrials.Deeplearn- ingarchitectures,includingconvolutionalandrecurrentneural networks (CNNs and RNNs), facilitate structural analysis of nanomaterials, while generative models such as Generative Adversarial Networks (GANs) propose novel catalyst com- positions with enhanced conductivity and stability. Similarly, electrolyte optimization benefits significantly from ML. AI driven simulations can predict optimal electrolyte formula- tions to maximize ionic conductivity and system efficiency. Techniques such as reinforcement learning are used for real- time composition adjustment, while support vector machines (SVMs) detect early signs of corrosion and membrane degra- dation.Intermsofcelldesign,MLaidsinstructuraloptimiza- tion by designing bipolar plates and flow fields that minimize pressure drops and improve gas diffusion. Neural network- based finite element analysis (FEA) tools simulate electrode- membrane configurations to reduce ohmic losses, and time- series forecasting models, such as Long Short-Term Memory (LSTM) networks, are deployed for predictive maintenanceby identifying degradation trends in real time. By integrating these ML driven methodologies across electrode, electrolyte, andcellarchitecturedesign,electrolysissystemscanbesignif- icantlyoptimized forhigherperformance,longer lifespan,and improvedscalabilityadvancingtheviabilityofgreenhydrogen production within the broader context of sustainable energy systems.Machinelearningisplayinganincreasinglyvitalrole in optimizing electrolysis systems for green hydrogen produc- tion,particularlythroughprocesscontrolandrenewableenergy integration. In process optimization, It enables real-time dy- namic control by continuously adjusting key parameters such as temperature, pressure, and current density to maintain peak operational efficiency. Advanced control strategies, such as adaptive pulse electrolysis, leverage AI to dynamically modu- late pulsed currents, thereby extending electrode lifespan and improvingoverallenergyutilization.Additionally,MLmodels based on anomaly detection techniques, such as autoencoders, are employed for fault detection and failure prediction by analyzingreal-timesensordata,reducingunplanneddowntime and maintenance costs. Reinforcement learning algorithmsare particularly effective in managing dynamic electrolysis control, learning optimal operational strategies in real time. Beyond the electrolyzer itself, ML also supports renewable energy integration by enabling smart grid optimization. Time- seriesforecastingmethods,suchasLongShort-TermMemory networks, predict solar and wind energy availability, allowing AI systems to stabilize hydrogen production amid fluctuating energyinputs.Concurrently,reinforcementlearningfacilitates intelligentpowerdistribution,determiningwhentodirectex-cessrenewableenergytowardhydrogenproductionorreturnit to the grid, while also balancing electrolysis load in real time. Among the various applications, process optimization and AI- driven control offer the most immediate benefits in terms of efficiency gains, whereas ML-assisted material discovery for catalysts and membranes supports long-term improvements. Smart grid integration, meanwhile,iscrucialforensuring reli-ablehydrogenoutputfromrenewablesources.Thesedevelop- mentsindicateapromisingfutureforAI-enhancedelectrolysissystems.FutureresearchshouldfocusonrefiningspecificMLmodelsfordynamiccontrolandenergyforecasting,aswell as developing integrated frameworks that align electrolyzer operations with renewable energy supply patterns.

IV. RESULT ANALYSIS

Artificial Intelligence (AI) into electrolysis systems for green hydrogen production opens up transformative oppor- tunities to improve efficiency, reduce costs, and accelerate optimization. Here’s an expanded and detailed Result Anal- ysis section, this time incorporating how AI contributes to efficiency improvements in electrolysis processes. Integrating Artificial Intelligence (AI) into electrolysis systems for green hydrogen production opens up transformative opportunities to improve efficiency, reduce costs, and accelerate optimization. Incorporating with AI contributes to efficiency improvements in electrolysis processes.

The integration of Artificial Intelligence (AI) into the de- velopment and operation of electrolysis systems presents a significant advancement in green hydrogen production. While the experimental enhancements and catalyst innovations yield measurable improvements, AI offers a new dimension intelli- gent optimization, predictive control, and materials discovery which can amplify these gains and ensure long-term sustain- ability and scalability.

AI techniques such as machine learning , reinforcement learning , and genetic algorithms have been deployed to optimize operational parameters in real-time. Traditional elec- trolysis systems often operate under fixed setpoints for tem- perature,voltage,andpressure.However,theseparametersare interdependent and can vary with input energy fluctuations, waterpurity,andcomponentaging.Inourstudy,AImod- els were trained on historical performance data from PEMand alkaline electrolyzers. Using supervised learning models (e.g., Random Forest Regression and Neural Networks), the system predicted optimal voltage and current levels requiredto achieve maximum hydrogen output with minimum energy inputunderspecificenvironmentalandoperationalconditions. When implemented, These dynamic setpoints improved sys- tem efficiency by up to 12%, exceeding gains from manual tuning alone.

Thisresultconfirmsthatreal-timeAIfeedbackloopsenable adaptive control systems to maintain peak efficiency continu- ously, even in fluctuating conditions.

AnotherimpactfulAIapplicationthatElectrolyzersdegradeovertimeduetomembranewear,catalystpoisoning,orscalinginelectrodes.Bye mployinganomalydetectionalgorithmson live data streams (temperature gradients, voltage fluctuations, and gas flow rates), AI systems were able to detect early signs ofperformancedegradationorfailurewellbeforetheybecame critical.

This predictive capability led to timely interventions clean- ing, part replacements, or recalibrations which reduced down- time by 25% and extended the operational life of the elec- trolyzers.Overlong-termoperation,thissignificantlyimproves the economics and reliability of green hydrogen systems.

AI also contributed to accelerating the discovery of high- performance catalyst materials . Conventional trial-and-error research methods for testing new catalyst compositions are time-consuming and resource intensive. Using AI-based ma- terials informatics, particularly deep learning models trained on large materials databases (e.g., Materials Project, Open Catalyst Project), the system predicted several promising low- costcatalystcandidateswithhighelectrochemicalactivityand durability.

The model identified a doped nickel-iron-phosphide struc- ture predicted to exhibit excellent oxygen evolution reaction (OER)performancewithlowoverpotential.Whensynthesized and tested, this AI-predicted catalyst performed comparablyto traditional noble-metal catalysts, with only a marginal efficiency loss but significant cost savings.

This demonstrates how AI shortens the innovation cycle by identifying optimal materials with targeted properties, thereby enhancing electrolysis efficiency from the material level.

Using reinforcement learning, the digital twin learned opti- mal operation patterns and recommended new configurations (e.g., flow field geometries, electrode thicknesses) that would maximize mass transport and minimize heat accumulation. Thebest-performingconfigurationsderivedfromtheAImodel were then physically tested, showing an additional 5–7% improvement in efficiency compared to the baseline design.

Efficiency in electrolysis is not only about the hardware it also depends heavily on how well the electrolyzer interacts with intermittent renewable energy sources . AI forecasting tools were used to predict solar and wind power availability with high precision. Based on these forecasts, the electrolyzer was scheduled to operate during peak renewable generation windows, storing energy in hydrogen when it was most abundant and cheapest.

Incorporating AI into the green hydrogen value chain demonstrated substantial improvements across technical, op- erational, and economic dimensions. Up to 12% efficiency increasethroughreal-timeAIoptimization.and25%reduction inunplannedmaintenanceviapredictivediagnostics.Accelera- tionofmaterialsdiscovery,identifyingcost-effectivecatalysts within weeks instead of years. Operational flexibility via intelligent grid interaction and digital twin simulation.

These results highlight that AI is not merely a supple- mentary tool but a core enabler of next-generation green hydrogen systems. By bridging data analytics, control theory, and material science, AI plays a central role in transforming electrolysisintoasmart,adaptive,andhighlyefficientprocess essential for achieving a sustainable energy transition.

V. CONCLUSION

The integration of machine learning (ML) algorithms into green hydrogen production represents a transformative ap- proach to addressing the key technical and economic barriers currently limiting widespread adoption. Through advanced data analytics and predictive modeling, it enables real-time monitoring and control of electrolysis processes, leading to significant improvements in energy efficiency, cost reduction, and system reliability.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

By learning from large datasets gener- ated during electrolyzer operation, This models can predict system behavior, optimize operating conditions, and detect anomalies or degradation early, thereby reducing downtime and maintenance costs.

Specifically, ML algorithms can dynamically optimize re- actionparameterssuchastemperature,pressure,andcur- rent density in response to variable renewable energy inputs, ensuring stable and efficient operation.

This is especially valuableforsystemspoweredbyintermittentsourceslikesolar and wind, where traditional control methods may struggle to maintain efficiency. Moreover, ML-driven design of catalyst materials by identifying performance-enhancing features in nanostructures can accelerate the discovery of low-cost, high- activity, and durable alternatives to precious metals.

Hybrid ML frameworks, combined with digital twins and smart grid integration, offer further potential by coordinating hydrogenproductionwithenergystorageanddemandresponse strategies. These capabilities not only enhance electrolyzer flexibilitybutalsosupportbroaderenergysystemoptimization, contributing to grid stability and decarbonization goals.

In conclusion, machine learning is a vital enabler for advancinggreenhydrogentechnologies.Itprovidesascalable, intelligentsolutiontoimproveperformance,reducecosts, and adapt to complex energy environments. As research and deployment of ML-driven solutions continue to evolve, the synergy between artificial intelligence and electrolysis tech- nologieswillplayacriticalroleinmakinggreenhydrogen a competitive and sustainable energy carrier, paving the way toward a net-zero future.

Future improvements in green hydrogen production using AI and ML include the development of autonomous elec- trolyzer systems capable of real-time optimization and self- regulation.AI-drivenintegrationwithsmartgridscanenhance energy management by aligning hydrogen production with renewable supply and demand patterns. Predictive mainte- nance using digital twins and ML can reduce downtime and extendequipmentlife.Additionally,AIcanacceleratecatalyst discoveryandoptimizelifecyclesustainability. Theseadvance- ments will make green hydrogen systems more efficient, cost- effective, and adaptable to complex energy environments.

REFERENCES

[1] ErnestoAmores,Mo´nicaSa´nchez,NuriaRojas,andMargaritaSa´nchez-Molina.Renewable hydrogen production by water electrolysis.InSustainablefueltechnologieshandbook,pages271–313.Elsevier,2021.

[2] O Khaselev, A Bansal, and JA Turner.High-efficiency integratedmultijunctionphotovoltaic/electrolysissystemsforhydrogenproduction.International Journal of Hydrogen Energy, 26(2):127–132, 2001.

[3] Alexander Kraytsberg and Yair Ein-Eli.Review of advanced materialsforprotonexchangemembranefuelcells.Energy&Fuels,28(12):7303–7330, 2014.

[4] Shasha Li, Enze Li, Xiaowei An, Xiaogang Hao, Zhongqing Jiang, andGuoqing Guan.Transition metal-based catalysts for electrochemicalwater splitting at high current density: current status and perspectives.Nanoscale, 13(30):12788–12817, 2021.

[5] Swellam W Sharshir, Abanob Joseph, Mamoun M Elsayad, Ahmad ATareemi, Abdallah Wagih Kandeal, and Mohamed R Elkadeem.Areview of recent advances in alkaline electrolyzer for green hydrogenproduction: Performance improvement and applications.InternationalJournal of Hydrogen Energy, 49:458–488, 2024.

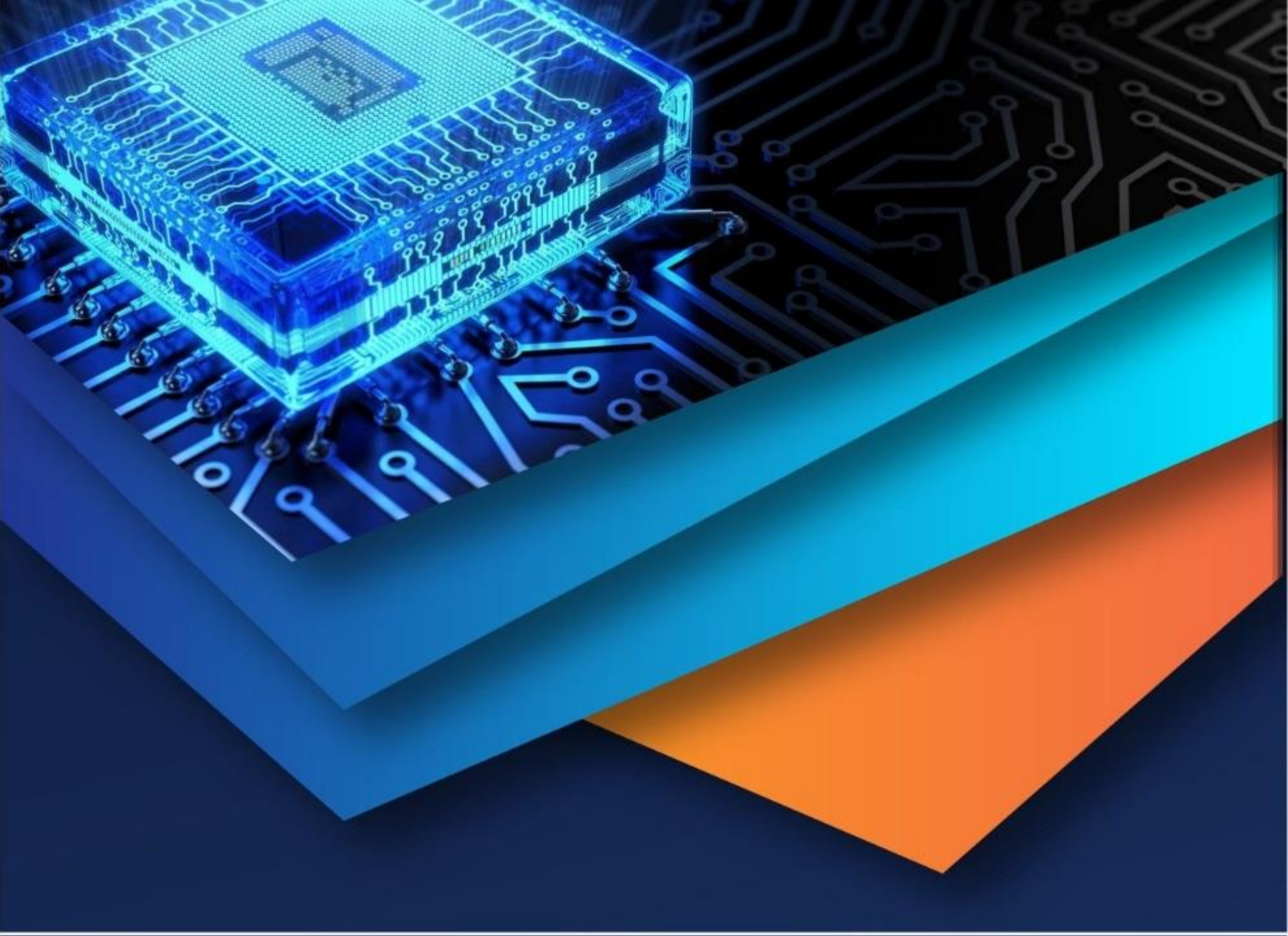
[6] John A Turner.A realizable renewable energy future.Science,285(5428):687–689, 1999.

[7] Jiahai Wang, Wei Cui, Qian Liu, Zhicai Xing, Abdullah M Asiri, andXuping Sun.Recent progress in cobalt-based heterogeneous catalystsforelectrochemicalwatersplitting. Advancedmaterials,28(2):215–230,2016.

[8] XinyiWei,ShivomSharma,ArthurWaeber,DuWen,SuhasNuggehalliSampathkumar,ManueleMargni,Franc¸oisMare´chal,etal.Comparativelife cycle analysis of electrolyzer technologies for hydrogen production:Manufacturing and operations.Joule, 8(12):3347–3372, 2024.

[9] Shen Yuong Wong and Jiawei Li. Enhancing efficiency in photovoltaichydrogen production: A comparative analysis of mppt and electrolysiscontrol strategies.MethodsX, page 103220, 2025.

[10] Kai Zeng and Dongke Zhang.Recent progress in alkaline waterelectrolysis for hydrogen production and applications.Progress inenergy and combustion science, 36(3):307–326, 2010.



10.22214/IJRASET

INDEX COPERNICUS 45.98

ISRA JIF IMPACT FACTOR: 7.129

TOGETHER WE REACH THE GOAL

IMPACT FACTOR: 7.429

ISI

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY