ACS MATERIALS LETTERS

www.acsmaterialsletters.org

PERSPECTIVE

Challenges in Electrolyzer Performance Evaluation for Green Hydrogen Production

Published as part of ACS Materials Letters virtual special issue "Materials for Water Splitting".

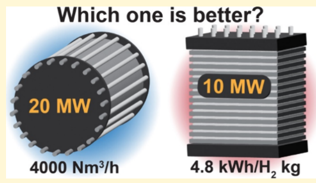
Seok-Jin Kim, Javeed Mahmood, Phil Woong Kang, Zhonghua Xue, and Cafer T. Yavuz*

Cite This: *ACS Materials Lett.* 2024, 6, 3168−3175

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: **The transition to sustainable energy increasingly relies on hydrogen gas produced by water electrolysis. Current performance metrics for electrolyzers, typically measured in megawatts or kilowatts, inadequately capture the full scope of the system efficiency and hydrogen output rates. The gap between academic and industrial evaluations can distort the perceived effectiveness of these technologies. This Perspective proposes a refined dual-metric evaluation system that integrates both energy efficiency (kWh/kg H_2) and production rate (Nm^3/h) to provide a balanced view of performance. A standardized framework similar to that for photovoltaic technologies is suggested to enable transparent comparisons and support advancements in electrolyzer design. Emphasizing the need for consistent testing conditions, the framework aims to ensure that the evaluations of the electrodes, stacks, and overall systems remain reliable across various operational scenarios. Adopting such a comprehensive evaluation approach is essential for accurately communicating the capabilities of water electrolyzers and propelling the widespread use of green hydrogen.**



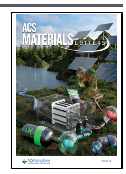
1. INTRODUCTION

Hydrogen gas is a versatile energy carrier, with applications ranging from energy storage and power generation cells to chemical production.[1,2] This versatility has fueled a surge in research on hydrogen generation by water electrolysis. The transition toward green hydrogen production is crucial for the implementation of a hydrogen-centric energy future. Advancements in this field led to the creation of three promising electrolysis systems: alkaline water electrolyzers (AWE), anion exchange membrane water electrolyzers (AEMWE), and proton exchange membrane water electrolyzers (PEMWE). These systems aim to enhance energy efficiency and offer economically feasible alternatives for hydrogen production.[3,4] The possibility of improvements is heavily dependent on the design of the electrolyzer as well as the performance and endurance of electrodes.[5] As a result, there has been intense research to develop both efficient and stable catalysts, with rigorous testing and evaluation at the cell level, while adding to a growing knowledge base.[6−9] In industry, the scale of water electrolysis projects is rapidly expanding, with ventures ranging from 10−20 MW to planned GW projects.[10]

Despite the overwhelming research output, skepticism among researchers regarding the validity of reported advances in electrolysis technology and the associated literature has led to rigorous discussion and sharp criticism. This would be a healthy practice in moderation, but prolonged and heated disagreements and disbelief over metrics and measures could inadvertently stall the progress toward establishing a sustainable hydrogen economy. This Perspective aims to address the technical measurement challenges in hydrogen production by encouraging collaboration between industry and academia to address the issues of establishing standardized metrics. In addition to providing a groundwork for a widely acceptable evaluation, we anticipate that our Perspective will unravel a broader impact on the educational value and open dialogue in asking the right questions about electrolytic water splitting. We hope that our discussion will enable cross-discipline participation toward a renewable-energy-powered future.

Current performance metrics for electrolyzers, typically measured in megawatts or kilowatts, inadequately capture the full scope of the system efficiency and hydrogen output rates.

Received: March 28, 2024
Revised: June 9, 2024
Accepted: June 12, 2024
Published: June 21, 2024



https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

2. THE LIMITATION OF ELECTROLYZER PERFORMANCE AS THE SOLE METRIC

Power ratings commonly measure electrolyzer performance, but it can be tricky to rely solely on this metric (Figure 1). Typically, electrolyzer performance is defined by the amount of electricity required to produce hydrogen (activity, kWh/Nm^3), the rate of hydrogen production (capacity, Nm^3/h), and how long it lasts (lifespan, measured by the overpotential increase in units of mV/1000 h). However, these numbers are interdependent and heavily influenced by the measurement conditions. For example, an efficiency of 4.8 kWh/H_2 kg does not precisely indicate how fast hydrogen is produced (Figure 1). The production rate can be increased by consuming more electricity; however, this results in a decreased efficiency. Stability over time, on the other hand, has the potential to alter the amount of power consumed, even if the production rate remains the same.

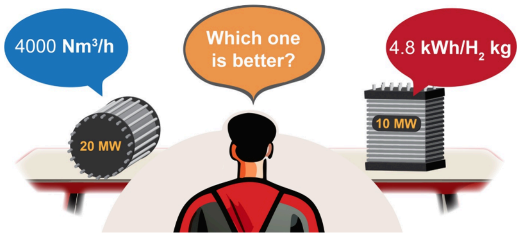


Figure 1. Comparative analysis limitations are due to insufficient performance data and a lack of a detailed environmental context.

Watt's law indicates that the power consumed (W, energy per unit time) is equal to the voltage applied (V) multiplied by the current (I). The efficiency improves with the proportion of electrons used to produce hydrogen at a specific voltage increase.[11] Therefore, electrolysis efficiency (measured in terms of kWh/kg of H_2 or Nm^3) represents the ratio of hydrogen produced to the power applied. Let us assume that a water electrolyzer with a capacity of 20 MW is deployed. When the news breaks, this will be received positively, because of the scale. However, the scale does not immediately reveal the amount of electrical energy (kWh) required to produce 1 kg of hydrogen or its production rate. If the efficiency of the 20 MW electrolyzer is lower than that of the 10 MW system, building two of the more efficient 10 MW systems would obviously be preferable.

Since electrolytic performance tests are conducted at different temperatures, it is practically challenging to compare the values based only on the production rate (Nm^3/h) or efficiency (kWh/Nm^3). One evidence of this issue is that academic research protocols are predominantly at room temperature, while industry often conducts tests between 50 °C and 80 °C. This leads to selective data reporting, which may be advantageous in marketing but may greatly exaggerate performance, in terms of technological viability. In addition, depending on the operating conditions like electrolyte concentration and temperature, factors such as catalysts and stack design can impact electrolysis efficiency.[8] For example, alkaline electrolysis works better with a higher concentration of potassium hydroxide electrolyte. A higher concentration of ions in a solution increases its conductivity, lowers the electrical resistance, and facilitates electrochemical reactions at the electrodes. As a result, hydrogen and oxygen production rates increase because of the favorable kinetics at the respective electrodes. Furthermore, higher temperatures allow for greater hydrogen production, because of the endothermic nature of water electrolysis.[12] While increasing the temperature and electrolyte concentration seems straightforward, it can lead to corrosion and durability issues for the electrode and stack materials if not properly managed. Therefore, water electrolysis performance data should be standardized by categorizing the competing data according to the system structure and testing conditions under similar conditions.

> This Perspective aims to address the technical measurement challenges in hydrogen production by encouraging collaboration between industry and academia to address the issues of establishing standardized metrics.

3. PRODUCTION RATE: WHY IT MATTERS

The electrolysis efficiency, often expressed in kWh per kg of H_2, enables one to estimate hydrogen production costs based on electricity prices (Figure 2). However, the variation in industrial operations raises the question of whether hydrogen pricing can be genuinely derived from a simple calculation. The market price for hydrogen is influenced by many factors, including capital expenditure (CAPEX) associated with infrastructure investments and the variable nature of operational expenditure (OPEX). CAPEX can be projected with some certainty, even with fluctuating material costs.[13] However, the OPEX is subject to significant variations, based on production scheduling (such as capitalizing on off-peak surplus electricity) and output volumes. Fixed costs, including labor, maintenance, administration, and leasing expenses, are consistent, regardless of the production level. Thus, the efficiency of a hydrogen production process, in terms of both time and quantity, can drastically affect the actual market price.

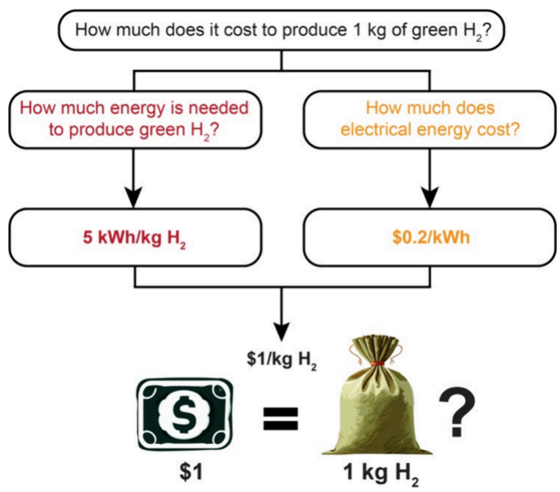


Figure 2. Calculating green hydrogen production prices by considering the efficiency and electricity prices.

A complex tradeoff exists between production speed and energy efficiency, as faster production can often lead to increased energy consumption per kilogram of hydrogen produced (Figure 3). If overlooked, this inverse relationship could result in operational inefficiencies and risk the competitiveness of

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

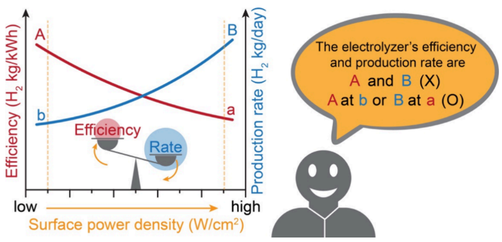


Figure 3. Relationship diagram showing the inverse proportion between hydrogen evolution efficiency and production rate, according to the surface power density. When presenting the performance of a water electrolyzer, it is appropriate to discuss the efficiency and production rate together under the same power density conditions.

green hydrogen in the market. In order to present favorable techno-economics, production efficiency is commonly reported using values at low power densities, while production rate values from high power densities are chosen. It is common sense that these two critical values must be obtained at the same power density at which the plant is planned to operate.

Another crucial factor is the electrode size. Larger electrodes can enhance hydrogen generation rates and energy efficiency, while reducing losses.[14] However, they also introduce challenges, such as increased internal resistance and uneven electron distribution over large areas. Strategically stacking multiple smaller electrode pairs can be an effective approach for improving the overall system performance. The variability in the performance of stacked electrode configurations is highly influenced by their design and needs constant optimization through new designs. Challenges exist in the development of stack design, where advancement should focus on the electrode size, configuration, or both to achieve optimal performance.

4. TECHNICAL ISSUES IN ELECTROLYZER EVALUATIONS

4.1. Electrode Testing. Electrocatalyst performance evaluation requires electrode testing, which typically involves a three-electrode system consisting of a working electrode, counter electrode, and reference electrode. Linear sweep voltammetry (LSV), cyclic voltammetry (CV), and chronoamperometry measurements are conducted under specific electrolyte conditions.[15] Despite being a routine analysis, numerous variables often distort performance, with many subtle variations that affect the overall outcome.

A significant issue, for example, arises during the *iR* (internal resistance) drop correction process, which is crucial for accurate data interpretation in electrochemical reactions. Incorrect *iR* drop correction can lead to inaccurate results. Anantharaj et al. have reported[16] guidelines for precisely correcting *iR* drops, highlighting several key aspects: resolving confusion about whether to apply correction before or after activity normalization, considering the overall uncompensated resistance (R_u) data, and the necessity to avoid partial correction when a full 100% correction is possible. Adhering to these guidelines is essential for a proper *iR* drop correction.[16] Additionally, Zheng et al. have proposed methods for correct *iR* compensation, underscoring the concerns of the community over *iR* correction issues.[17]

Beyond the *iR* correction, the purity of the measuring solutions significantly impacts the outcomes. For example, the Fe contamination in KOH electrolytes used for alkaline water electrolysis might enhance the OER performance,[18,19] whereas employing Pt as a counter electrode may cause inaccurate data.[20] Furthermore, the uniformity of the catalyst dispersion and its loading on the electrode surface can alter the performance, necessitating the continuous evaluation of catalyst performance in all planned configurations, from half-cell setups to actual stacks in large-scale water electrolysis applications.

4.2. Stack Evaluation. The transition from a single-cell electrolyzer to a stack configuration is crucial for demonstrating the feasibility of scaling up water electrolysis technology while minimizing efficiency and production rate losses. To avoid underestimation or overestimation, it is important to evaluate stack electrolyzers within a specified range of operational parameters. These operational parameters depend significantly on efficiency losses due to parasitic factors in noncatalytic component designs.[12]

One significant stack issue is the unwanted currents that bypass the intended path (also known as Shunt currents), which significantly impact the efficiency and longevity of electrolyzer systems, especially when the stack size or input power increases.[21] Recent advancements in AWE stack design have aimed to reduce electrolyte resistance through a zero-gap configuration. However, this has led to substantial shunt current losses, with reports indicating that such losses can account for up to 75.4% of the total electrical energy input in a 3 MW industrial-scale AWE stack.[22] Moreover, shunt currents have a detrimental effect on the durability of the electrodes and metallic cell components. For instance, uneven current distribution can expose metallic catalysts in cathodes to oxidation-prone potential windows, because of the low current density zones.[23] Similarly, shunt currents can induce metal decomposition or pitting in metallic components, as modeled by Burney and White.[24] Design strategies such as elongating the internal electrolyte channel length can help to mitigate these issues but may also increase pressure drops and energy consumption for pumping.[25,26] To minimize vulnerability to uneven electrical fields, it is advisible to optimize the design of electrodes/bipolar plates and to avoid metallic components in the electrolyte flow channels.

For water electrolyzers, addressing gas bubble formation is another critical aspect of a stack design. Gas production from a liquid can lead to issues such as reduced local current density, catalyst degradation, and gas crossover, because of the occupation of reaction sites by gas bubbles.[27,28] It is essential to carefully consider when borrowing stack designs from fuel cell systems, which typically convert gas to liquid. For instance, serpentine flow channels can dramatically interrupt the flow when gas bubbles are present.[29] Intuitively, modifying the flow field with concave or convex texturing, and incorporating multiple inlets and outlets, can help regulate electrolyte flow and mitigate bubble formation.[30−32] However, this approach might still create stagnant or circulating flow areas for large-area electrodes. Fang et al. have shown by experimental comparisons of stack electrolyzers that have smaller electrode areas with multiple stacks can more effectively curtail bubble formation and are preferable for continuous operation at high current densities.[33] Operating the electrolyzers at higher pressures can also enhance bubble kinetics within the cell.[34,35]

Lastly, the linear series configuration employed in most contemporary stack electrolyzers can exacerbate parasitic losses. Designers should incorporate features that reduce the shunt current and optimize bubble kinetics to enhance efficiency and extend operational longevity under targeted conditions. The

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

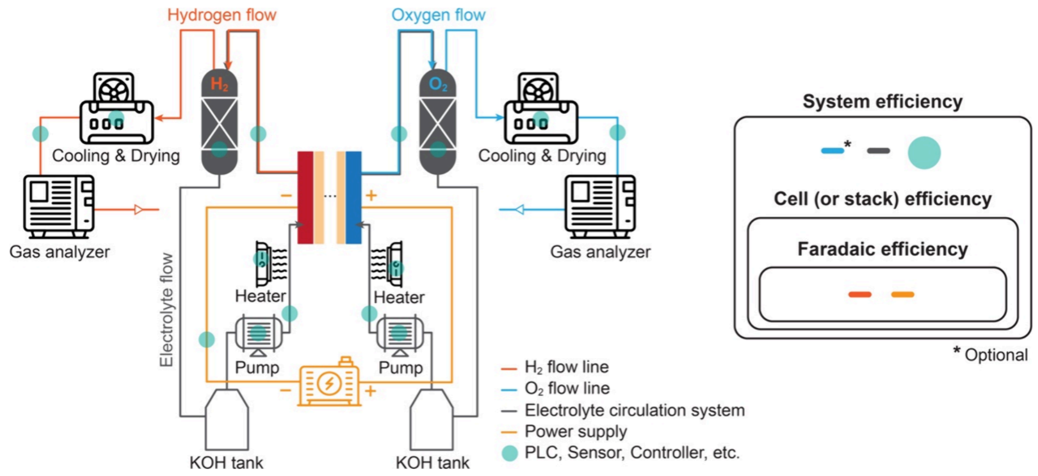


Figure 4. Schematics of an alkaline water electrolysis system with efficiency categories. The hydrogen and oxygen flows are depicted by orange and sky-blue lines, respectively. The alkaline electrolyte is illustrated in gray, whereas the electrical power input is highlighted in yellow. Cyan circles denote additional electrical control components, such as programmable logic controllers (PLCs) and sensors.

necessity of additional components, such as cathodic protection systems, may vary, depending on the specific operational conditions, particularly in the case of an off-grid setup or a system that frequently shuts down.[36,37]

4.3. Complete System Evaluation. The performance of an electrolyzer stack typically improves at higher electrolyte temperatures due to favorable thermodynamics, increased electron mobility, and enhanced ionic conductivity, all of which contribute to hydrogen production at lower overpotentials. However, when an improved performance is assumed at an electrolyte temperature of 80 °C, it can be challenging to determine whether the gains in stack efficiency outweigh the additional energy input required to maintain the temperature. To obtain realistic and practical efficiency estimates, it is necessary to analyze the total energy consumption of the entire system, in relation to the amount of hydrogen produced.

A correct reference could be found in car engines. Automobile fuel efficiency is typically expressed as the distance traveled per unit of fuel consumed. This approach simplifies the efficiency evaluation by focusing on the energy input and the ensuing performance while not needing factors, such as the weight of the vehicle, wheel size, or design attributes. This enables us to estimate the energy efficiency of a vehicle based on its reported fuel economy, eliminating the need for a detailed analysis of engine mechanics.

A similar strategy is appropriate for a hydrogen production system. An accurate system efficiency measurement should directly weigh the energy input against the hydrogen output. Instead of focusing only on the enthalpic performance of the electrocatalyst inside the stack, it is crucial to understand that various additional energy requirements influence hydrogen production:[12] the energy necessary for electrolyte circulation, temperature control, dehydration of produced gas, and overall system maintenance (Figure 4).

If we solely examine stack efficiency and ignore the additional energy demands from the rest of the system, there is a risk of using excessive energy, undermining the success of a project. As the automotive industry has sought to improve fuel economy by enhancing engine performance, using lightweight materials, optimizing cylinder technology, and developing brake energy regeneration systems, water electrolysis systems should incorporate engineering advancements on key components to boost overall efficiency.

5. IDEAL SET OF PERFORMANCE EVALUATION PARAMETERS

Considering all of the information needed for proper assessment of a water electrolyzer, we propose a set of benchmark standards for comparing performance to guide academic research and industrial development toward a unified approach to advancing this technology. Table 1 lists the most important criteria for the electrodes, electrolyzer stacks, and general efficiency of a complete system.

For electrodes, the metrics must include overpotential at a given current density, stability over time, as measured by the degradation rate, and faradaic efficiency at a specific voltage. In addition, the measurement conditions, such as the temperature and electrolyte concentration, must be well documented.

When electrolyzer stacks are evaluated, the critical factors are the stack efficiency in kilograms of hydrogen produced per kilowatt-hour, hydrogen purity percentage, operating temperature, pressure, stability quantified as the performance degradation rate, and production rate corresponding to a specific efficiency.

Finally, the overall energy efficiency of the hydrogen production system is measured by examining the stack, purification, and other components. Other metrics include the production rate linked to the stack performance, purity of hydrogen gas, operational temperature and pressure ranges, and long-term stability.

6. OUTLOOK

Although water electrolysis has been around since the experiments of Adriaan Paet van Troostwijk and Johan Rudolph Deiman in 1789,[38] there is still a remarkable lack of standardization in measuring and reporting the performance of electrolytic hydrogen production systems. This oversight may stem in part from the seemingly straightforward nature of the electrolytic hydrogen generation process upon the application of electrical energy, which may have resulted in a less rigorous exploration of the efficiency metrics. However, in the face of skepticism regarding green hydrogen and the need to realize

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

Table 1. Suggested Performance Metrics for the Electrolyzer Component That Is Evaluated

Electrode (Catalyst)[a]		
technical parameter	units[b]	indispensable remarks
overpotential of hydrogen (or oxygen) evolution reaction (HER/OER)	mV	at specific current density (mA/cm^2)
degradation rate (stability)	mV/h	at specific current density (mA/cm^2) and operating hours (h)
Faradaic efficiency	%	at specific applied voltage (V)

Stack[c]		
technical parameter	units[b]	indispensable remarks
stack energy consumption	H_2 kg/kWh	correlated with experimental and assumed production rate (kg/day)
hydrogen purity	%	correlated with batch or continuous production rate
stack I−V curve	A and V	
operating pressure (inlet)	bar	representative cell pressure
degradation rate	mV/h	at a given current density (mA/cm^2)
hydrogen production rate	H_2 kg/h	with specific stack efficiency, experimental or assumed amount

System[d]		
technical parameter	units[b]	indispensable remarks
total system energy efficiency (stack + purification + others)	H_2 kg/kWh	with a specific production rate
hydrogen production rate	H_2 kg/h	with specific stack efficiency
hydrogen purity	%	correlated with production rate
operating time	h	
system stability	H_2 kg/kWh/h	with hydrogen purity

[a]Measurement conditions to be included in all reporting: temperature, electrolyte concentration, justification of iR-correction, geometrical electrode area, and rotating rpm (if rotating disk electrode, RDE). [b]The proposed unit is the most commonly used and may be replaced by another internationally accepted one. [c]Measurement conditions to be reported for all parameters: temperature, electrolyte, stack size, and active electrode area. [d]Measurement conditions are needed in all parameters: temperature, electrolyte, stack size, active electrode area, operating current density, turn on−off frequency, and ramp-up and ramp-down frequency.

genuinely sustainable environmental solutions, it is critical to establish standardized measurements and efficiencies.

In this Perspective, we have outlined the inadequacy of using a single parameter to describe the performance of water electrolysis. We suggest that both the efficiency and production rate must be considered concurrently, especially when the power density is the same. Additionally, we segmented the discussion into electrode, stack, and system units to highlight critical components and technical challenges that are frequently overlooked, summarizing the essential elements in Table 1. This approach lays the groundwork for a reasonable comparison across various design and material choices, contributing to the development of efficient green hydrogen production technologies. Fair competition driven by transparent and rational metrics will undoubtedly accelerate the advent of a viable hydrogen economy. One successful example of such standardized practice is in photovoltaics research and development. Today, solar cells are widely available to consumers, and organizations such as the United States National Renewable Energy Laboratory (NREL) systematically evaluate their performance and make this information accessible, ensuring a certain level of standardization in the field.Both the efficiency and production rate must be considered concurrently, especially when the power density is the same.

Both the efficiency and production rate must be considered concurrently, especially when the power density is the same.

AUTHOR INFORMATION

Corresponding Author

Cafer T. Yavuz − *Oxide & Organic Nanomaterials for Energy & Environment (ONE) Lab, Chemistry Program, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; KAUST Catalysis Center, Physical Sciences and Engineering (PSE) and Advanced Membranes & Porous Materials Center, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia;* orcid.org/0000-0003-0580-3331; Email: cafer.yavuz@kaust.edu.sa

Authors

Seok-Jin Kim − *Oxide & Organic Nanomaterials for Energy & Environment (ONE) Lab, Chemistry Program, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; KAUST Catalysis Center, Physical Sciences and Engineering (PSE) and Advanced Membranes & Porous Materials Center, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia;* orcid.org/0000-0002-6052-547X

Javeed Mahmood − *Oxide & Organic Nanomaterials for Energy & Environment (ONE) Lab, Chemistry Program, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; KAUST Catalysis Center, Physical Sciences and Engineering (PSE) and Advanced Membranes & Porous Materials Center, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia;* orcid.org/0000-0002-9159-3336

Phil Woong Kang − *Oxide & Organic Nanomaterials for Energy & Environment (ONE) Lab, Chemistry Program, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; Advanced Membranes & Porous Materials Center, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia*

Zhonghua Xue − *Oxide & Organic Nanomaterials for Energy & Environment (ONE) Lab, Chemistry Program, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; KAUST Catalysis Center, Physical Sciences and Engineering (PSE) and Advanced Membranes & Porous*

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

Materials Center, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsmaterialslett.4c00690

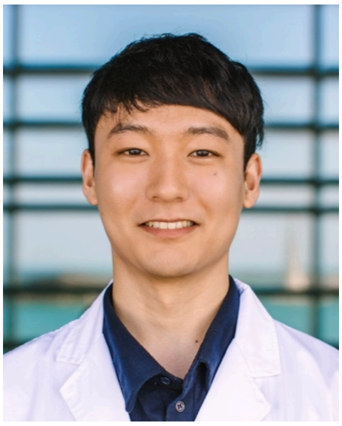
Author Contributions

The manuscript was written through the contributions of all authors. CRediT: **Seok-Jin Kim** conceptualization, data curation, formal analysis, investigation, methodology, writing-original draft, writing-review & editing; **Javeed Mahmood** conceptualization, data curation, formal analysis, writing-original draft, writing-review & editing; **Phil Woong Kang** formal analysis, validation, writing-review & editing; **Zhong-hua Xue** validation, writing-review & editing; **Cafer T. Yavuz** conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, writing-review & editing.

Notes

The authors declare no competing financial interest.

Biographies



Seok-Jin Kim is a Research Scientist at King Abdullah University of Science and Technology (KAUST), specializing in catalysis and materials. He earned his combined Master's and Doctoral degrees from the Ulsan National Institute of Science and Technology (UNIST), South Korea, in 2019. His work includes developing robust electrocatalysts and high-efficiency materials for energy applications.

Javeed Mahmood is a Research Scientist at the King Abdullah University of Science and Technology (KAUST), Saudi Arabia. Before joining KAUST, he worked as a Research Assistant Professor at the Ulsan National Institute of Science and Technology (UNIST), South Korea. He received his Ph.D. from the School of Energy and Chemical Engineering at UNIST in 2015. His current research interests include design and synthesis of novel heterogeneous catalysts and porous polymers for energy and environmental applications.

Phil Woong Kang received his Ph.D. in Chemical and Biomolecular Engineering from the Korea Advanced Institute of Science and Technology in 2023. He is currently a postdoctoral researcher at King Abdullah University of Science and Technology. His research focuses on developing electrolysis systems for alkaline water electrolysis and carbon dioxide reduction as sustainable energy storage technologies.

Zhonghua Xue received his Ph.D. in Chemistry from Shanghai Jiao Tong University, China, in March 2020. He is currently a Postdoctoral Researcher at the King Abdullah University of Science and Technology (KAUST), Saudi Arabia. His current research mainly focuses on designing and fabricating efficient catalysts for electrochemical reactions (e.g., water splitting and ammonia synthesis).

Cafer T. Yavuz is a Professor of Chemistry at KAUST, specializing in sustainable nano and porous materials chemistry for environmental applications. He received his Ph.D. in Chemistry from Rice University and conducted postdoctoral research at UC Santa Barbara. Prof. Yavuz

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

previously held academic positions at the Korea Advanced Institute of Science and Technology (KAIST). His research focuses on CO2 utilization, water treatment, and gas storage.

■ ACKNOWLEDGMENTS

This work was supported by the King Abdullah University of Science and Technology (KAUST).

■ REFERENCES

(1) Oliveira, A. M.; Beswick, R. R.; Yan, Y. S. A green hydrogen economy for a renewable energy society. *Curr. Opin. Chem. Eng.* **2021**, *33*, 100701.

(2) Zhang, H. J.; Maijenburg, A. W.; Li, X. P.; Schweizer, S. L.; Wehrspohn, R. B. Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting. *Adv. Funct. Mater.* **2020**, *30*, 2003261.

(3) Ursúa, A.; Gandía, L. M.; Sanchis, P. Hydrogen Production From Water Electrolysis: Current Status and Future Trends (vol 100, pg 410, 2012). *Proc. IEEE* **2012**, *100*, 811−811.

(4) Turner, J. A. Sustainable hydrogen production. *Science* **2004**, *305*, 972−974.

(5) Kjartansdóttir, C. K.; Nielsen, L. P.; Moeller, P. Development of durable and efficient electrodes for large-scale alkaline water electrolysis. *Int. J. Hydrogen Energy* **2013**, *38*, 8221−8231.

(6) Li, W.; Tian, H.; Ma, L.; Wang, Y.; Liu, X.; Gao, X. Low-temperature water electrolysis: fundamentals, progress, and new strategies. *Mater. Adv.* **2022**, *3*, 5598−5644.

(7) Franco, A.; Giovannini, C. Recent and Future Advances in Water Electrolysis for Green Hydrogen Generation: Critical Analysis and Perspectives. *Sustainability* **2023**, *15*, 16917.

(8) Pozio, A.; Bozza, F.; Nigliaccio, G.; Platter, M.; Monteleone, G. Development perspectives on low-temperature electrolysis. *ENEA* **2021**, *1*, 66−72.

(9) Kumar, S. S.; Lim, H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep.* **2022**, *8*, 13793−13813.

(10) Keddar, M.; Zhang, Z. F.; Periasamy, C.; Doumbia, M. L. Power quality improvement for 20 MW PEM water electrolysis system. *Int. J. Hydrogen Energy* **2022**, *47*, 40184−40195.

(11) Kweon, D. H.; Okyay, M. S.; Kim, S. J.; Jeon, J. P.; Noh, H. J.; Park, N.; Mahmood, J.; Baek, J. B. Ruthenium anchored on carbon nanotube electrocatalyst for hydrogen production with enhanced Faradaic efficiency. *Nat. Commun.* **2020**, *11*, 1278.

(12) Ju, W. B.; Heinz, M. V. F.; Pusterla, L.; Hofer, M.; Fumey, B.; Castiglioni, R.; Pagani, M.; Battaglia, C.; Vogt, U. F. Lab-Scale Alkaline Water Electrolyzer for Bridging Material Fundamentals with Realistic Operation. *ACS Sustain. Chem. Eng.* **2018**, *6*, 4829−4837.

(13) Zuo, Y.; Bellani, S.; Ferri, M.; Saleh, G.; Shinde, D. V.; Zappia, M. I.; Brescia, R.; Prato, M.; De Trizio, L.; Infante, I.; Bonaccorso, F.; Manna, L.; et al. High-performance alkaline water electrolyzers based on Ru-perturbed Cu nanoplatelets cathode. *Nat. Commun.* **2023**, *14*, 4680.

(14) Bashir, S. M.; Nadeem, M. A.; Al-Oufi, M.; Al-Hakami, M.; Isimjan, T. T.; Idriss, H. Sixteen Percent Solar-to-Hydrogen Efficiency Using a Power-Matched Alkaline Electrolyzer and a High Concentrated Solar Cell: Effect of Operating Parameters. *ACS Omega* **2020**, *5*, 10510−10518.

(15) Shih, A. J.; Monteiro, M. C. O.; Dattila, F.; Pavesi, D.; Philips, M.; da Silva, A. H. M.; Vos, R. E.; Ojha, K.; Park, S.; van der Heijden, O.; et al. Water electrolysis. *Nat. Rev. Methods Primers* **2022**, *2*, 84.

(16) Anantharaj, S.; Noda, S. drop correction in electrocatalysis: everything one needs to know! *J. Mater. Chem. A* **2022**, *10*, 9348−9354.

(17) Zheng, W. R. *iR* Compensation for Electrocatalysis Studies: Considerations and Recommendations. *ACS Energy Lett.* **2023**, *8*, 1952−1958.

(18) Márquez, R. A.; Kawashima, K.; Son, Y. J.; Castelino, G.; Miller, N.; Smith, L. A.; Chukwuneke, C. E.; Mullins, C. B. Getting the Basics Right: Preparing Alkaline Electrolytes for Electrochemical Applications. *ACS Energy Lett.* **2023**, *8*, 1141−1146.

(19) Son, Y. J.; Kawashima, K.; Wygant, B. R.; Lam, C. H.; Burrow, J. N.; Celio, H.; Dolocan, A.; Ekerdt, J. G.; Mullins, C. B. Anodized Nickel Foam for Oxygen Evolution Reaction in Fe-Free and Unpurified Alkaline Electrolytes at High Current Densities. *ACS Nano* **2021**, *15*, 3468−3480.

(20) Jerkiewicz, G. Applicability of Platinum as a Counter-Electrode Material in Electrocatalysis Research. *ACS Catal.* **2022**, *12*, 2661−2670.

(21) White, R. E.; Walton, C. W.; Burney, H. S.; Beaver, R. N. Predicting Shunt Currents in Stacks of Bipolar Plate Cells. *J. Electrochem. Soc.* **1986**, *133*, 485.

(22) Sakas, G.; Ibáñez-Rioja, A.; Pöyhönen, S.; Kosonen, A.; Ruuskanen, V.; Kauranen, P.; Ahola, J. Influence of shunt currents in industrial-scale alkaline water electrolyzer plants. *Renewable Energy* **2024**, *225*, 120266.

(23) Esfandiari, N.; Aliofkhazraei, M.; Colli, A. N.; Walsh, F. C.; Cherevko, S.; Kibler, L. A.; Elnagar, M. M.; Lund, P. D.; Zhang, D.; Omanovic, S.; et al. Metal-based cathodes for hydrogen production by alkaline water electrolysis: Review of materials, degradation mechanism, and durability tests. *Prog. Mater. Sci.* **2024**, *144*, 101254.

(24) Burney, H. S.; White, R. E. Predicting Shunt Currents in Stacks of Bipolar Plate Cells with Conducting Manifolds. *J. Electrochem. Soc.* **1988**, *135*, 1609.

(25) Bennett, W. R.; Hoberecht, M. A.; Lvovich, V. F. Analysis of shunt currents and associated corrosion of bipolar plates in PEM fuel cells. *J. Electroanal. Chem.* **2015**, *737*, 162−173.

(26) Qi, R.; Becker, M.; Brauns, J.; Turek, T.; Lin, J.; Song, Y. Channel design optimization of alkaline electrolysis stacks considering the trade-off between current efficiency and pressure drop. *J. Power Sources* **2023**, *579*, 233222.

(27) Cao, X.; Zhao, N.; Zhang, S.; Zhou, L.; Hu, Y.; Yun, J. Investigation of the hydrogen bubble effect on the overpotential in an alkaline water electrolyzer. *Int. J. Hydrogen Energy* **2024**, *49*, 47−57.

(28) Daoudi, C.; Bounahmidi, T. Overview of alkaline water electrolysis modeling. *Int. J. Hydrog. Energy* **2024**, *49*, 646−667.

(29) Wong, X. Y.; Zhuo, Y.; Shen, Y. Numerical Analysis of Hydrogen Bubble Behavior in a Zero-Gap Alkaline Water Electrolyzer Flow Channel. *Ind. Eng. Chem. Res.* **2021**, *60*, 12429−12446.

(30) Wang, T.; Wang, J.; Wang, P.; Wang, F.; Liu, L.; Guo, H. Non-uniform liquid flow distribution in an alkaline water electrolyzer with concave-convex bipolar plate (CCBP): A numerical study. *Int. J. Hydrogen Energy* **2023**, *48*, 12200−12214.

(31) Wang, T.; Wang, J.; Wang, P.; Ren, Z.; Peng, C. Electrolysis Visualization and Performance Evaluation Platform for Commercial-Sized Alkaline Water Electrolyzer. In *Proceedings of the 10th Hydrogen Technology Convention*, Vol. *1*; Sun, H., Pei, W., Dong, Y., Yu, H., You, S., Eds.; Springer Nature: Singapore, 2024; pp 390−400.

(32) Lopata, J. S.; Kang, S. G.; Cho, H. S.; Kim, C. H.; Weidner, J. W.; Shimpalee, S. Investigating influence of geometry and operating conditions on local current, concentration, and crossover in alkaline water electrolysis using computational fluid dynamics. *Electrochim. Acta* **2021**, *390*, 138802.

(33) Huang, D.; Zhong, Z.; Ai, X.; Hu, K.; Xiong, B.; Wen, Q.; Fang, J.; Cheng, S. Size design strategy for scaling up alkaline water electrolysis stack integrated with renewable energy source: A multiphysics modeling approach. *Energy Convers. Manag.* **2024**, *300*, 117955.

(34) Jang, D.; Cho, H.-S.; Kang, S. Numerical modeling and analysis of the effect of pressure on the performance of an alkaline water electrolysis system. *Appl. Energy* **2021**, *287*, 116554.

(35) Jang, D.; Choi, W.; Cho, H.-S.; Cho, W. C.; Kim, C. H.; Kang, S. Numerical modeling and analysis of the temperature effect on the performance of an alkaline water electrolysis system. *J. Power Sources* **2021**, *506*, 230106.

(36) Kim, Y.; Jung, S.-M.; Kim, K.-S.; Kim, H.-Y.; Kwon, J.; Lee, J.; Cho, H.-S.; Kim, Y.-T. Cathodic Protection System against a Reverse-Current after Shut-Down in Zero-Gap Alkaline Water Electrolysis. *JACS Au* **2022**, *2*, 2491−2500.

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175

(37) Tsukase, N.; Araki, T.; Haleem, A. A.; Nagasawa, K.; Kuroda, Y.; Mitsushima, S. Numerical simulation of the distribution of reverse currents in a practical alkaline water electrolysis stack immediately after electrolysis. *Int. J. Hydrogen Energy* **2024**, *49*, 701−712.
(38) Smolinka, T.; Bergmann, H.; Garche, J.; Kusnezoff, M. The history of water electrolysis from its beginnings to the present. In *Electrochemical Power Sources: Fundamentals, Systems, and Applications*, Smolinka, T., Garche, J., Eds.; Elsevier, 2022; Chapter 4, pp 83−164.

https://doi.org/10.1021/acsmaterialslett.4c00690
ACS Materials Lett. 2024, 6, 3168−3175