

The Activity–Stability Paradox of Ruthenium Oxide in Acidic Oxygen Evolution Reaction

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Abstract: Ruthenium dioxide (RuO₂) is among the most active catalysts for the acidic oxygen evolution reaction (OER) and remains a leading candidate for proton exchange membrane water electrolyzers. However, its exceptional activity is often accompanied by rapid degradation, creating a long-standing activity–stability paradox that limits practical deployment. Increasing evidence suggests that this tradeoff is not merely coincidental but often arises from the same structural and electronic features that promote OER kinetics, including strong Ru–O covalency, lattice oxygen participation, oxygen-vacancy formation, oxidation-state evolution, and surface reconstruction. This Perspective studies the mechanistic origins of RuO₂ degradation and highlights how catalytic activity and instability are coupled under acidic OER conditions. Recent advances demonstrate that durable RuO₂ catalysts are unlikely to emerge from maximizing activity or stability independently. Instead, this Perspective suggests that durable RuO₂ catalysts should be designed through controlled metastability, where electronic structure, Ru–O bonding, oxygen-lattice dynamics, defect/vacancy chemistry, surface reconstruction, and interfacial interactions are regulated within a controlled and preferably reversible operating window. This approach provides a practical framework for balancing catalytic activity and long-term stability in RuO₂-based acidic OER catalysts.

Keywords: acidic oxygen evolution; Ruthenium dioxide; activity–stability tradeoff

1. Introduction

Proton exchange membrane (PEM) water electrolysis is considered as one of the most promising technologies for hydrogen production because of its compact design, rapid response, and ability to operate at high current densities [1]. However, the oxygen evolution reaction (OER) at the anode remains a major bottleneck because of its sluggish kinetics. This challenge is further intensified in PEM electrolyzers by the highly corrosive acidic operating environment, especially under anodic polarization, which accelerates catalyst degradation. As a result, only a limited number of electrocatalysts can maintain sufficient activity and stability under acidic OER conditions [2]. Although extensive research has been devoted to earth-abundant acidic OER electrocatalysts, noble-metal oxides remain the most reliable candidates for practical PEM water electrolysis [3]. IrO₂-based catalysts are usually regarded as a more stable benchmark for acidic OER, but the scarcity and high cost of iridium continue to motivate the search for alternative catalytic systems [4,5]. Thus, RuO₂ remains highly attractive because it shows exceptional acidic OER activity and generally lower noble-metal cost than Ir-based oxides, being approximately 7.5 times cheaper than Ir [6].



RuO₂ is therefore positioned between two competing expectations. On one hand, it offers outstanding acidic OER activity with lower cost compared to Ir-based oxides. On the other hand, its durability under acidic anodic operation remains insufficient for long-term PEM water electrolysis [6,7]. This contrast has inspired extensive efforts to improve Ru-based catalysts performance through multiple approaches, such as doping, defect engineering, heterostructure construction, amorphization, and support interaction [8–13]. However, many reported strategies mainly extend apparent stability under specific testing conditions, while the deeper connection between activity-enhancing surface dynamics and degradation is still not fully resolved.

The central challenge is that the catalytic activity and instability of RuO₂ are likely not independent properties. Many surface processes that enhance its OER activity, including flexible Ru–O bonding, lattice oxygen participation, oxygen-vacancy formation, oxidation-state evolution, and surface reconstruction, can also accelerate overoxidation, Ru dissolution, and irreversible structural degradation [14–19]. This creates an important paradox in acidic OER electrocatalysis: the same dynamic surface chemistry that improves OER activity may simultaneously reduce catalyst durability [20–22].

Several recent reviews have discussed the mechanistic links between Ru–O covalency, lattice oxygen participation, surface reconstruction, and degradation in RuO₂-based acidic OER catalysts [23–30]. However, these reviews mainly summarize degradation mechanisms and stabilization strategies, whereas the present Perspective connects these processes within a coherent design framework based on controlled metastability. In this framework, activity and instability are not treated as entirely independent properties, but as outcomes of the same dynamic surface processes. Rather than viewing stability as the complete suppression of structural change, or activity as simply maximizing surface dynamics, we argue that durable RuO₂ catalysts require dynamic surface evolution to remain within a limited, controlled, and preferably reversible range. The key challenge is therefore not simply to choose between activity and stability, but to regulate the extent, reversibility, and spatial distribution of metastable surface states before they evolve into irreversible Ru dissolution or structural collapse. This framework provides a basis for interpreting recent advances in doping, defect engineering, support design, proton-transfer regulation, interfacial engineering, and operando mechanistic evidence, while also offering a clearer roadmap for future Ru-based acidic OER catalyst design. Rather than providing a comprehensive review of all Ru-based acidic OER catalysts, we focus on the fundamental origins of this paradox and discuss recent design strategies that balance catalytic activity and durability. Finally, we outline future directions for developing highly active and stable RuO₂ electrocatalysts for acidic water electrolysis.

2. Origins of the Exceptional Acidic OER Activity of Ruthenium dioxide

The exceptional acidic OER activity of RuO₂ originates from a combination of favorable electronic structure, strong and flexible Ru–O covalency, rapid charge-transfer capability, and dynamic surface chemistry under anodic conditions [13]. Unlike many transition-metal oxides that suffer from poor conductivity or excessively strong oxygen binding, RuO₂ possesses an electronic environment that allows efficient adsorption and transformation of oxygenated intermediates while maintaining fast electron transport [31]. These features have made RuO₂ one of the most intensively studied catalysts for acidic water oxidation and a key reference material for understanding OER mechanisms in noble-metal oxides [32]. At the same time, increasing experimental and theoretical evidence suggests that the high activity of RuO₂ cannot be fully explained using a static catalyst model. Under acidic OER conditions, the catalyst surface may continuously undergo changes in oxidation state, oxygen coordination, hydration, defect concentration, and local ordering [33–35]. As a result, the highly active state of RuO₂ often appears closely connected to dynamic structural and electronic behavior during operation rather than to the pristine crystalline phase alone.

2.1. Electronic Structure and Ru–O Covalency

RuO₂ crystallizes in a rutile-type structure and exhibits significantly higher electrical conductivity than many conventional transition-metal oxides. This conductive nature facilitates rapid electron transport during OER and minimizes kinetic limitations associated with charge transfer. More importantly, the strong hybridization between Ru 4d orbitals and O 2p states produces a highly covalent Ru–O framework that strongly influences catalytic activity. The adsorption energies of key OER intermediates, including *OH, *O, and *OOH, are highly sensitive to the electronic structure of the catalyst surface. It is well understood that the catalysts that bind these intermediates too weakly often suffer from insufficient surface activation, whereas excessively strong adsorption may inhibit intermediate conversion and product desorption. RuO₂ benefits from a relatively balanced interaction with oxygenated intermediates, placing it among the most active oxide catalysts for acidic OER [36]. This balance

partly explains why RuO₂ generally exhibits lower overpotentials and faster reaction kinetics compared with many non-noble-metal oxides under acidic conditions.

In addition, the strong Ru–O covalency provides substantial redox flexibility during operation. Surface Ru centers can readily undergo oxidation-state evolution under anodic polarization, allowing the catalyst surface to dynamically respond to changes in applied potential and local reaction environment. Such flexibility is often beneficial for proton-coupled electron-transfer processes involved in OER. However, this same feature also makes the Ru–O framework more susceptible to structural evolution under highly oxidative conditions. Recent studies increasingly describe Ru–O covalency as a double-edged characteristic that simultaneously supports catalytic activity and promotes structural instability when oxygen exchange or Ru overoxidation becomes excessive [37,38].

2.2. Lattice Oxygen Participation and Dynamic Oxygen Chemistry

The OER activity of RuO₂ has traditionally been interpreted using the adsorbate evolution mechanism (AEM), in which oxygen formation proceeds through sequential adsorption and transformation of *OH, *O, and *OOH intermediates on surface Ru sites [39]. Although this mechanism successfully explains many aspects of OER catalysis, increasing evidence suggests that lattice oxygen may also directly participate in oxygen evolution under certain conditions [40]. In the lattice oxygen mechanism (LOM), oxygen atoms from the catalyst lattice contribute directly to O–O bond formation. This process may partially bypass the scaling limitations associated with adsorbate-mediated pathways and therefore accelerate OER kinetics (Figure 1) [17]. The relatively flexible Ru–O framework and fast oxygen exchange characteristics of RuO₂ are believed to facilitate this dynamic oxygen participation. Consequently, many recent studies have intentionally promoted oxygen-vacancy formation, defect-rich structures, or lattice activation to enhance catalytic activity [37,41–43]. In addition to the conventional AEM/LOM description, recent studies have also discussed an oxide-path mechanism (OPM) for RuO₂-based catalysts. In this pathway, O–O bond formation proceeds through oxide-bridged or peroxide-like surface intermediates associated with the Ru–O framework, without necessarily requiring net lattice oxygen release or irreversible oxygen-vacancy accumulation. The OPM therefore provides another way to describe oxygen evolution on dynamically evolved RuO₂ surfaces and further highlights that oxygen-lattice chemistry can contribute to activity in different ways depending on the local Ru–O bonding environment and applied potential. Recent studies suggest that OPM-type pathways may be favored by specific local geometries, including adjacent metal sites with suitable interatomic distances, often reported in the range of 2.4–2.9 Å, together with electronic structures that stabilize peroxide-like intermediates while avoiding excessive lattice oxygen oxidation [44,45].

However, lattice oxygen participation or OPM-type pathways should not be considered universal features of all RuO₂ catalysts. The relative contribution of AEM, LOM, and OPM depends strongly on crystallographic facet, local coordination environment, defect concentration, hydration state, electrolyte composition, and applied potential [46]. For example, highly defective or partially hydrated RuO_x-like surfaces may exhibit more pronounced oxygen exchange behavior than well-ordered rutile RuO₂ facets [18,47]. Similarly, stronger lattice oxygen participation is often observed at higher anodic potentials where the catalyst lattice becomes increasingly activated [48].

Oxygen vacancies are also connected to this dynamic oxygen chemistry. Controlled vacancy formation can modify local electronic structure, improve oxygen mobility, and generate more reactive catalytic environments [49,50]. These effects may increase catalytic activity by facilitating oxygen exchange and accelerating surface redox processes. However, oxygen vacancies should not be viewed simply as beneficial defects. Their influence depends on vacancy type, concentration, distribution, and whether the catalyst lattice can accommodate vacancy formation without severe structural disruption. Excessive or irreversible oxygen-vacancy accumulation may destabilize the Ru–O framework and promote irreversible surface evolution, which later becomes a primary driver of catalyst degradation [51].

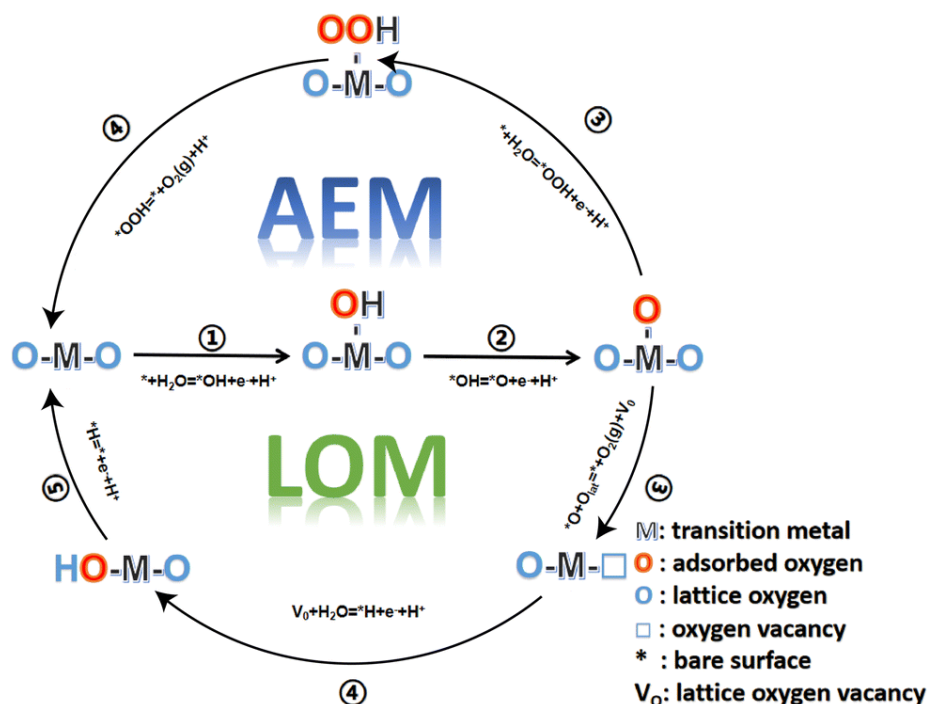


Figure 1. General schematic comparison of AEM and LOM pathways for acidic OER on RuO₂-based catalysts. Reprinted with permission from Ref. [52], under the terms of the Creative Commons Attribution-NonCommercial 3.0 Unported Licence (CC BY-NC 3.0). Copyright 2023, The Author(s). Published by the Royal Society of Chemistry.

2.3. Dynamic Surface Reconstruction and Metastable Active States

Another important characteristic of RuO₂ is that its surface may not remain identical to the initially synthesized structure. Under anodic polarization, RuO₂/RuO_x surfaces can undergo oxidation-state evolution, hydration or deprotonation, local disorder, oxygen-lattice activation, and partial reconstruction [11,19,53–56]. Operando studies suggest that the structure–activity–stability relationship of RuO₂-based catalysts depends strongly on the catalyst structure under working conditions rather than only on the pristine material. Under OER conditions, a large fraction of OH groups in RuO_x can become deprotonated, producing highly oxidized active surfaces in which oxidation involves not only Ru centers but also the oxygen lattice itself. Such oxygen-lattice activation appears to be more pronounced in amorphous RuO_x than in crystalline RuO₂ and is believed to contribute to both enhanced activity and reduced stability [11]. Similar trends have also been observed experimentally when comparing amorphous and crystalline RuO₂ catalysts, where highly hydrated or low-crystallinity RuO_x surfaces showed stronger oxygen-intermediate interactions and higher activity but lower stability under acidic OER conditions [57].

Recent studies further suggest that dissolution and reconstruction are closely connected processes. Rather than occurring as independent processes, metal dissolution, surface restructuring, changes in surface composition, and modification of local electronic density may proceed simultaneously during electrochemical cycling [54]. Combined experimental and computational work showed that metal dissolution from RuO₂ and Ru_{1-x}Ti_xO₂ surfaces can induce surface reconstruction, modify electronic density distributions, and generate new active sites, thereby changing the activation barriers of OER steps [19]. In some cases, dynamically reconstructed RuO_x-like surfaces may expose more accessible Ru sites, facilitate oxygen exchange, and promote faster oxygen evolution kinetics. However, these reconstructed states are not always stable. Potential-dependent evolution of RuO₂ surfaces may initially generate highly active distorted RuO₃-like environments, while further evolution at higher anodic potentials can promote overoxidation, dissolution, and the formation of less active RuO₄-like species (Figure 2) [53]. At the same time, the relationship between activity and dissolution should not be oversimplified. Activity and stability may depend strongly on crystallographic orientation, morphology, defect density, and pretreatment history. Some studies have shown that corrosion-sensitive sites may dissolve during early operation while catalytically active sites remain, suggesting that OER activity and dissolution are not always directly coupled [54].

Therefore, the catalytically active state of RuO₂ under acidic OER conditions is likely an operando-evolved structure rather than the original crystalline phase alone. Instead of behaving as a fully static oxide, RuO₂ may function as a continuously evolving catalytic interface in which Ru–O covalency, oxygen mobility, oxidation-state evolution, and surface structural changes occur simultaneously. Importantly, many of these dynamic processes are

closely associated with the exceptional OER activity of RuO₂. Structural flexibility, oxygen exchange capability, and redox-active surface states may collectively accelerate oxygen evolution kinetics. However, when reconstruction, oxygen-lattice activation, or oxidation-state evolution become excessive or irreversible, the same processes may weaken lattice stability and promote long-term catalyst degradation. Thus, the dynamic nature that gives RuO₂ its remarkable catalytic activity also establishes the mechanistic basis of the activity–stability paradox discussed in the following section.

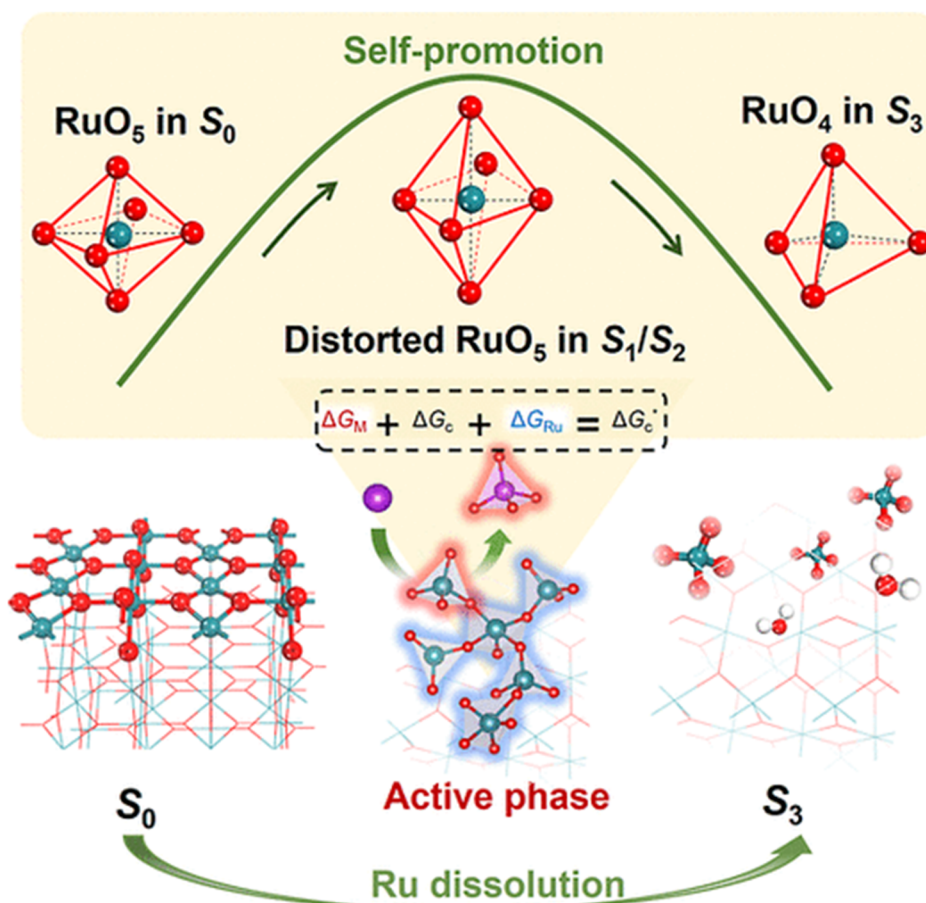


Figure 2. Schematic illustration of potential-dependent surface evolution of RuO₂ during acidic OER. Dynamic reconstruction and Ru dissolution may initially generate distorted RuO₅-like metastable active states, whereas excessive evolution at higher anodic potentials promotes overoxidation and formation of less active RuO₄-like species, Reproduced from Ref. [53] with permission from the American Chemical Society. Copyright 2025, American Chemical Society.

3. When Activity Drives Instability: Structural Origin of Ruthenium Dioxide Degradation

The exceptional acidic OER activity of RuO₂ is closely linked to its dynamic structural and electronic behavior under anodic conditions. However, as discussed above, many of the same features responsible for rapid oxygen evolution may also accelerate catalyst degradation. Increasing evidence suggests that RuO₂ instability is not simply caused by independent corrosion processes occurring alongside catalysis. Instead, degradation appears intrinsically coupled to the catalytic mechanism itself. Thus, highly active RuO₂ surfaces often operate in metastable states that progressively evolve toward overoxidation, dissolution, and structural collapse under prolonged acidic OER conditions [53].

3.1. Ru Overoxidation and Dissolution

One major degradation pathway of RuO₂ is the formation of highly oxidized Ru species at strong anodic potentials. Surface Ru centers can evolve beyond the relatively stable Ru⁴⁺ state, and further oxidation may generate soluble RuO₄ or related RuO_xH_y species, leading to gradual loss of active Ru from the catalyst surface [58,59]. Theoretical studies also suggest that Ru dissolution can proceed through surface-bound oxyhydroxide intermediates, such as RuO₂(OH)₂ and RuO₃OH, before forming soluble RuO₄ species [59,60]. Computational work on RuO₂(110) has shown that OER and Ru dissolution may share common metastable intermediates, and

that some dissolution intermediates can even lower the OER overpotential [59]. This supports the view that catalytic turnover and degradation can be mechanistically coupled, although their interaction depends on the catalyst surface and reaction conditions.

3.2. Lattice Oxygen Activity and Ru–O Covalency

Overoxidation is also closely connected to lattice oxygen activity. Operando X-ray absorption spectroscopy (XAS) studies show that RuO_x surfaces become highly oxidized near OER potentials, with oxidation involving not only Ru centers but also the oxygen lattice [11]. This oxygen-lattice activation is especially strong in amorphous RuO_x and has been linked to its high activity but lower stability [57]. Therefore, oxygen-lattice activation is a double-edged process. While it can improve OER activity, it may also weaken the Ru–O framework and accelerate catalyst dissolution when it becomes excessive.

Importantly, lattice oxygen participation should not be viewed as inherently detrimental. Recent studies increasingly suggest that the stability of RuO_2 depends less on whether lattice oxygen participates in OER than on whether oxygen exchange remains controlled and reversible. When oxygen vacancies are rapidly replenished and excessive Ru overoxidation is avoided, lattice oxygen participation can sustain high catalytic activity without causing severe structural degradation. These findings indicate that uncontrolled or irreversible lattice oxygen loss, rather than lattice oxygen participation itself, is the primary factor responsible for catalyst degradation [61].

Additionally, the role of Ru–O covalency is central to this coupling. Strong Ru–O hybridization helps to promote OER kinetics, but excessive Ru–O covalency can activate lattice oxygen and make the surface more vulnerable to oxygen loss, overoxidation, and dissolution [33,62]. This explains why strategies that simply maximize oxygen mobility or lattice oxygen activity may improve initial activity but reduce long-term durability. Recent stabilization studies support this interpretation. Nb-, Si-, V-, and related dopant strategies improve durability mainly by regulating Ru–O covalency, suppressing excessive lattice oxygen participation, or preventing Ru overoxidation, while maintaining sufficient activity (Figure 3) [33,58,63]. Therefore, the key challenge is not to eliminate lattice oxygen activity completely, but to keep Ru redox chemistry and oxygen-lattice participation within a controlled and reversible range.

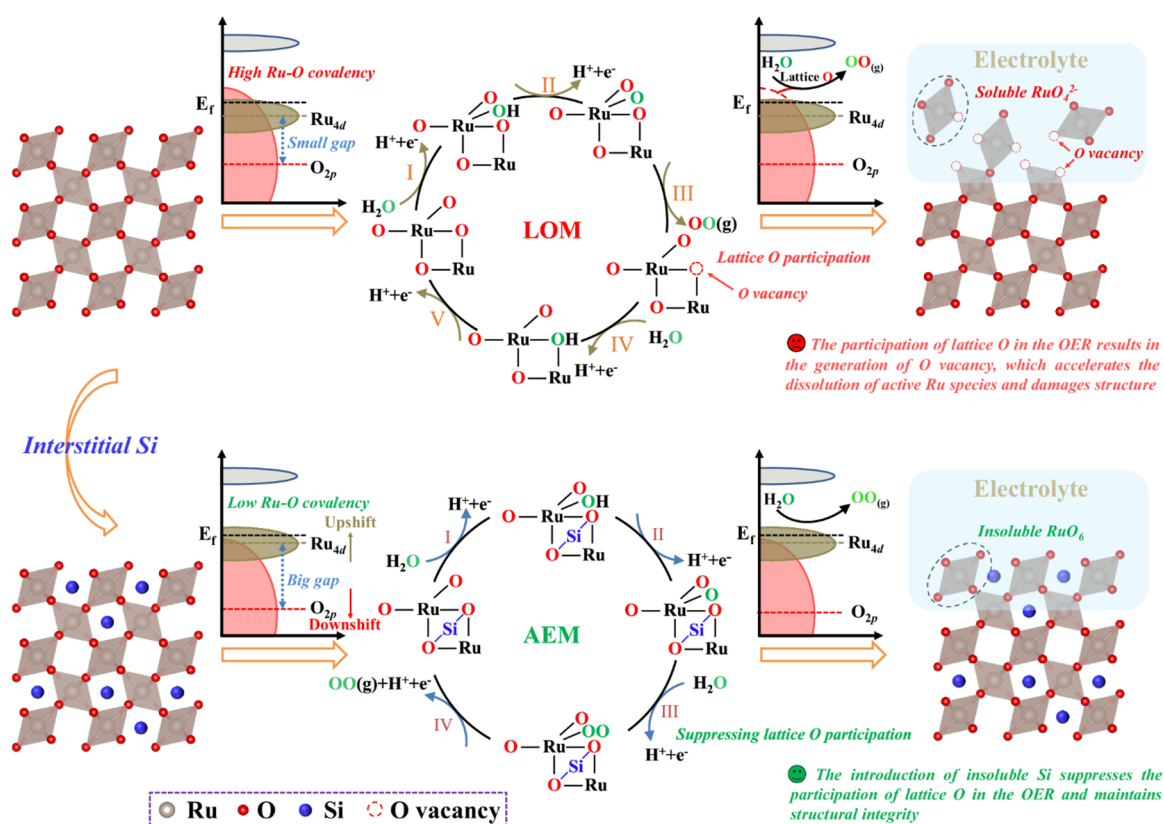


Figure 3. Schematic illustration of the activity–stability tradeoff in RuO_2 during acidic OER. Strong Ru–O covalency promotes lattice oxygen participation, but also accelerates oxygen-vacancy formation, Ru dissolution, and structural degradation. Si incorporation regulates Ru–O covalency, suppresses excessive lattice oxygen activation, and improves durability. Reproduced from Ref. [33] under the terms of the Creative Commons Attribution 4.0 International Licence (CC BY 4.0). Copyright 2024, The Author(s).

Surface reconstruction represents another important aspect of RuO₂ degradation under acidic OER conditions. As discussed earlier, RuO₂ surfaces rarely remain completely static during operation. Instead, anodic polarization can induce hydration, local amorphization, oxygen-vacancy generation, Ru redistribution, and partial restructuring of the surface lattice [19,64]. In some cases, these reconstructed RuO_x-like surfaces may initially enhance catalytic activity by exposing more flexible coordination environments, increasing oxygen exchange, or generating more reactive Ru sites. However, surface reconstruction should not always be interpreted as a beneficial activation process. Whether it improves or weakens catalyst stability depends on the extent and nature of the structural changes, and whether they remain controlled during operation. Moderate restructuring may help accommodate oxygen exchange and Ru redox changes without severe lattice disruption. In contrast, excessive reconstruction can progressively destabilize the Ru–O framework, especially under highly oxidative conditions where oxygen-vacancy accumulation, Ru overoxidation, and lattice oxygen loss become more pronounced. Under such conditions, metastable active states may eventually evolve toward irreversible disorder and dissolution of active Ru species into the electrolyte [53].

3.3. Surface Reconstruction, Defects, and Vacancy-Mediated Instability

Defects and oxygen vacancies play a similarly dual role in RuO₂-based acidic OER catalysts. Defect engineering and vacancy generation are widely used to improve OER activity because they can modify the electronic structure, increase oxygen mobility, and facilitate adsorption or oxygen exchange processes [65,66]. Nevertheless, highly defective RuO₂ surfaces are often thermodynamically less stable than well-ordered rutile structures. Recent work comparing cation and anion vacancies in RuO₂ further demonstrated that defect type and concentration strongly influence the balance between activity and durability, highlighting that not all vacancies contribute equally to catalyst performance [67]. Consequently, strategies based solely on maximizing defect density or oxygen mobility may improve initial catalytic activity while simultaneously increasing long-term instability.

These observations further reinforce an important concept emerging throughout recent RuO₂ studies: the challenge is not simply to maximize catalytic activity, oxygen exchange, or structural flexibility. Instead, the key requirement is to maintain these dynamic processes within a controlled and reversible range. As a result, highly durable RuO₂ catalysts are likely those capable of sustaining sufficient surface flexibility for rapid OER kinetics while preventing irreversible lattice evolution and Ru dissolution during long-term acidic operation.

3.4. Probing Dynamic Bonding and Surface Evolution

Although significant progress has been made in understanding acidic OER on RuO₂, several mechanistic questions remain open. Distinguishing between AEM, LOM, OPM, and the onset of Ru dissolution is not straightforward because these processes may occur over similar potential ranges and may involve related oxygenated intermediates. In addition, Ru oxidation-state evolution, lattice oxygen activity, surface reconstruction, and dissolution can occur at the same time during OER operation. Therefore, mechanistic conclusions based on one characterization method alone should be treated carefully [11,60,68].

Operando and isotope-sensitive techniques have been central to clarifying these dynamic processes. Operando XAS can track changes in Ru oxidation state, Ru–O coordination, and local bonding, although it often averages surface and bulk contributions. Raman and infrared spectroscopies can provide information on Ru–O vibrations and adsorbed oxygen intermediates, but peak assignments may be ambiguous without complementary evidence [69,70]. Isotope-labeling experiments, especially ¹⁸O-labeling combined with differential electrochemical mass spectrometry (DEMS), are particularly useful for identifying the oxygen source in evolved O₂ and assessing lattice oxygen participation [15,17,71,72]. However, even isotope-labeling experiments require careful interpretation because isotope exchange, surface hydration, and mixed reaction pathways can complicate the analysis. For this reason, the most convincing mechanistic studies usually combine several tools, such as XAS, isotope-labeling/DEMS, vibrational spectroscopy, post-operando structural analysis, and dissolution measurements.

Computational studies provide an important link between these experimental observations and atomic-scale mechanisms. Density functional theory (DFT) has been widely used to examine Ru–O covalency, OER intermediate adsorption, oxygen-vacancy formation, and Ru dissolution pathways [72,73]. Surface Pourbaix and related thermodynamic analyses can help predict stable surface states under different potential and pH conditions, while ab initio molecular dynamics can provide insight into hydration, proton transfer, and surface restructuring under more realistic environments [74]. Nevertheless, these models still simplify the real PEMWE environment, where high current density, local transport effects, ionomer contact, and continuous reconstruction occur together. Future progress will therefore require closer integration between operando characterization and advanced simulations. This combined approach is essential for identifying which surface changes are reversible and

beneficial, which changes lead to irreversible degradation, and how RuO₂ catalysts can be designed according to the concept of controlled metastability.

4. Design Strategies for Balancing Activity and Stability in RuO₂ Catalysts

The mechanistic insights discussed above suggest that highly active and durable RuO₂ catalysts are unlikely to be achieved by optimizing activity and stability independently. Strategies that only increase activity may accelerate lattice oxygen activation, reconstruction, and Ru dissolution, while strategies that only suppress structural evolution may reduce the dynamic surface chemistry needed for fast OER kinetics. Therefore, future catalyst design should target an optimized balance between activity and durability, where Ru redox chemistry, oxygen exchange, and surface reconstruction are allowed to occur within a controlled and reversible range. In this context, metastability should not necessarily be viewed as an unfavorable or negative characteristic. Thus, a completely rigid catalyst surface may suppress some of the dynamic surface chemistry features required for efficient oxygen evolution, whereas excessive structural flexibility may accelerate dissolution and irreversible degradation. Consequently, recent research increasingly focuses on balancing activity and stability through controlled surface evolution rather than maximizing either property independently.

4.1. Regulating Ru–O Covalency, Lattice Oxygen Activity, and Oxidation-State Evolution

One major strategy for improving RuO₂ durability involves the careful design of the electronic structure and local coordination environment of ruthenium active sites. Since Ru overoxidation is strongly associated with catalyst dissolution, many recent studies have focused on controlling Ru–O covalency, oxygen-lattice activity, and oxidation-state evolution during operation to balance catalytic activity and durability. Recent evidence suggests that the stability of RuO₂ depends strongly on how Ru 4d–O 2p orbital interactions regulate oxygen redox activity, lattice oxygen participation, and surface reconstruction under OER conditions [42,75]. Because excessive oxygen exchange can trigger degradation, the goal is increasingly shifting from simply maximizing oxygen exchange toward maintaining controlled and reversible oxygen-lattice dynamics. Heteroatom doping can redistribute local charge density, stabilize Ru coordination environments, and moderate excessive lattice oxygen activation by tuning Ru–O covalency and oxygen redox behavior. Elements such as Ti, Ta, Sb, W, V, Ir, Sn, and Nb have been shown to regulate Ru–O bonding characteristics and improve catalyst stability while preserving substantial OER activity [37,38,58,63,76–80]. Similarly, recent studies demonstrated that combining lattice strain and dopant regulation can improve stability numbers while maintaining substantial OER activity, highlighting the importance of simultaneously controlling local electronic structure and oxygen coordination [21]. Li et al. demonstrated that balancing Ru–O covalency rather than fully suppressing oxygen redox activity was found to improve both activity and durability simultaneously [81]. Recent work by Ruitao and co-workers on Ru/TiMnO_x further demonstrated that electronic-structure regulation through Ti/Mn incorporation can simultaneously enhance stability and optimize metal–oxygen covalency (Figure 4) [82]. In addition to heteroatom doping, interface engineering offers an alternative route to regulate Ru–O chemistry without introducing foreign metal cations. Song et al. developed a sub-4 nm Ru–RuO₂ Schottky nanojunction (Ru–RuO₂–SN) in which the lattice strain and charge transfer induced by the metal–oxide junction increase the work function and optimize the local electronic structure, favoring the OPM mechanism and suppressing ruthenium overoxidation to soluble RuO₄ resulting in an exceptionally high stability number (6.7×10^6) comparable to Ir-based catalysts together with excellent PEMWE performance [68].

Taken together, these examples suggest that doping, strain, and interfacial engineering improve RuO₂ performance mainly by shifting the Ru–O bond environment into a balanced state. If the Ru–O interaction is too labile, the catalyst becomes prone to oxygen loss, Ru overoxidation, and dissolution. On the other hand, if it is too rigid, the surface may lose the redox flexibility required for rapid OER kinetics. Effective structural modification therefore aims to maintain Ru–O bonds that are sufficiently stable to preserve the oxide framework, but still flexible enough to support reversible oxygen exchange and catalytic turnover. From this perspective, the activity–stability relationship is not governed by increasing or decreasing Ru–O covalency alone, but by balancing Ru–O bond strength, Ru redox flexibility, and the reversibility of oxygen-lattice dynamics.

In many cases, the reversibility of oxygen exchange may be more important than simply minimizing lattice oxygen participation. Reversible lattice oxygen activity, dynamic oxygen-vacancy refilling, and controlled surface reconstruction can stabilize RuO₂ surfaces while maintaining rapid OER kinetics [47,75]. Representative strategies include facet and defect engineering that promote reversible lattice oxygen cycling, hydroxyl-spillover-induced oxygen-vacancy refilling using MoO_x clusters, and heteroatom doping that suppresses excessive Ru overoxidation while preserving controlled lattice oxygen redox [47,51,61,76,80]. Because these oxygen-lattice processes are coupled with proton-coupled electron-transfer steps during OER, the local proton-transfer environment also plays

an important role in controlling the stability of reactive Ru–O species. Bridged oxygen vacancies, WO_x -derived Brønsted acid sites, and F-mediated hydrogen-bond interactions can accelerate deprotonation steps, regulate Ru–O covalency, and suppress excessive Ru overoxidation [41,78,83–86]. These findings extend the structure–activity relationship beyond Ru–O covalency alone, showing that proton-transfer sites, oxygen-vacancy refilling pathways, and hydrogen-bond networks can also regulate the lifetime of reactive Ru–O species. Therefore, future RuO_2 catalyst design may depend less on suppressing dynamic surface chemistry and more on coordinating oxygen, proton, and defect dynamics within a controlled operating window.

Defect and vacancy engineering should also be considered within the same controlled-regulation framework. Oxygen vacancies in RuO_2 can modify the coordination environment of Ru centers, expose additional active sites, tune intermediate adsorption, and in some cases promote alternative OER pathways. Early defective RuO_2 studies showed that vacancies and low Ru–O coordination can improve intrinsic OER activity, while later work further demonstrated that stabilized or reversible oxygen vacancies can contribute to both activity and durability. However, vacancies are not automatically beneficial. If they are poorly stabilized or accumulate irreversibly, they may weaken Ru–O coordination, promote lattice oxygen loss, and accelerate structural degradation [16,66,77,87–89]. Therefore, the key issue is not simply increasing vacancy concentration, but controlling the type, stability, reversibility, and local environment of the vacancies during acidic OER. Overall, these strategies point to a general design rule: high activity requires dynamic Ru–O bonding and reversible oxygen/proton exchange, whereas long-term stability requires these processes to remain controlled before they evolve into irreversible vacancy accumulation, Ru overoxidation, and dissolution.

4.2. Support-Induced Stabilization and Interfacial Anchoring

Support engineering provides another route to control the dynamic evolution of RuO_2 -based catalysts under acidic OER conditions. The role of the support is no longer limited to increasing surface area or physically anchoring Ru species. Properly selected supports can modify the local electronic structure of Ru sites, regulate Ru oxidation states, tune Ru–O covalency, influence oxygen-lattice reactivity, and alter the dissolution behavior of RuO_x [65,82,90–96]. Accordingly, the support can act as an external regulator of RuO_2 metastability. A key concept emerging from recent studies is that strong electronic coupling between RuO_2 and conductive, corrosion-resistant supports can buffer the oxidation-state changes of Ru during OER. For example, WC-, Mn_3O_4 -, and Zn– SnO_2 -supported RuO_2 catalysts show support-to- RuO_2 electron transfer, which lowers the effective Ru oxidation state, suppresses excessive Ru overoxidation, and improves operational stability compared with unsupported RuO_2 [91,93,94]. Similarly, Wang et al. reported that defective TiO_2 supports enriched with oxygen vacancies can form a continuous interfacial band structure with RuO_2 , lowering the energetic barrier for $^*\text{OOH}$ formation while improving durability [65]. These examples suggest that supports may function as electron reservoirs that help prevent uncontrolled Ru oxidation while preserving sufficient surface reactivity for OER.

Support structure can also strongly influence catalyst behavior. In MnO_2 -supported Ru catalysts, the tunnel size of the MnO_2 polymorph was shown to control the strength of Ru–O–Mn interactions. An intermediate tunnel size provided the strongest metal–support interaction, improving both OER activity and resistance to Ru dissolution [92]. This indicates that support effects depend not only on chemical composition, but also on crystal structure, local oxygen geometry, and lattice compatibility. Beyond electronic effects, confinement engineering offers another way to control RuO_2 degradation. Honeycomb-like Sb-doped SnO_2 supports can spatially confine RuO_2 nanoparticles and locally enrich dissolved high-valence Ru species. This shifts the $\text{RuO}_2/\text{H}_2\text{RuO}_5$ equilibrium away from continuous Ru overoxidation and gives substantially improved stability without strongly changing the initial OER activity [95]. More recently, Zhou et al. reported that intrinsic metal–support interactions in Ru/ TiMnO_x electrodes can dynamically stabilize highly active Ru species during long-term OER operation, suggesting that some support systems may help regulate reversible structural evolution rather than simply resist structural change (Figure 4) [82].

These findings show that supports and heterointerfaces are not only passive anchoring platforms. They can regulate interfacial charge transfer, Ru oxidation pathways, lattice oxygen participation, and dynamic reconstruction of RuO_x surfaces. The effectiveness of support engineering strategy for stabilizing RuO_x catalysts depends strongly on the choice of support and the nature of the RuO_x /support interface. The support itself must remain stable under acidic anodic polarization while providing sufficient electronic and structural stabilization of Ru species during operation. Therefore, the goal is not simply to introduce a support, but to design a stable and well-matched interface that can regulate Ru oxidation, suppress dissolution, and preserve the dynamic surface chemistry required for rapid OER kinetics [97].

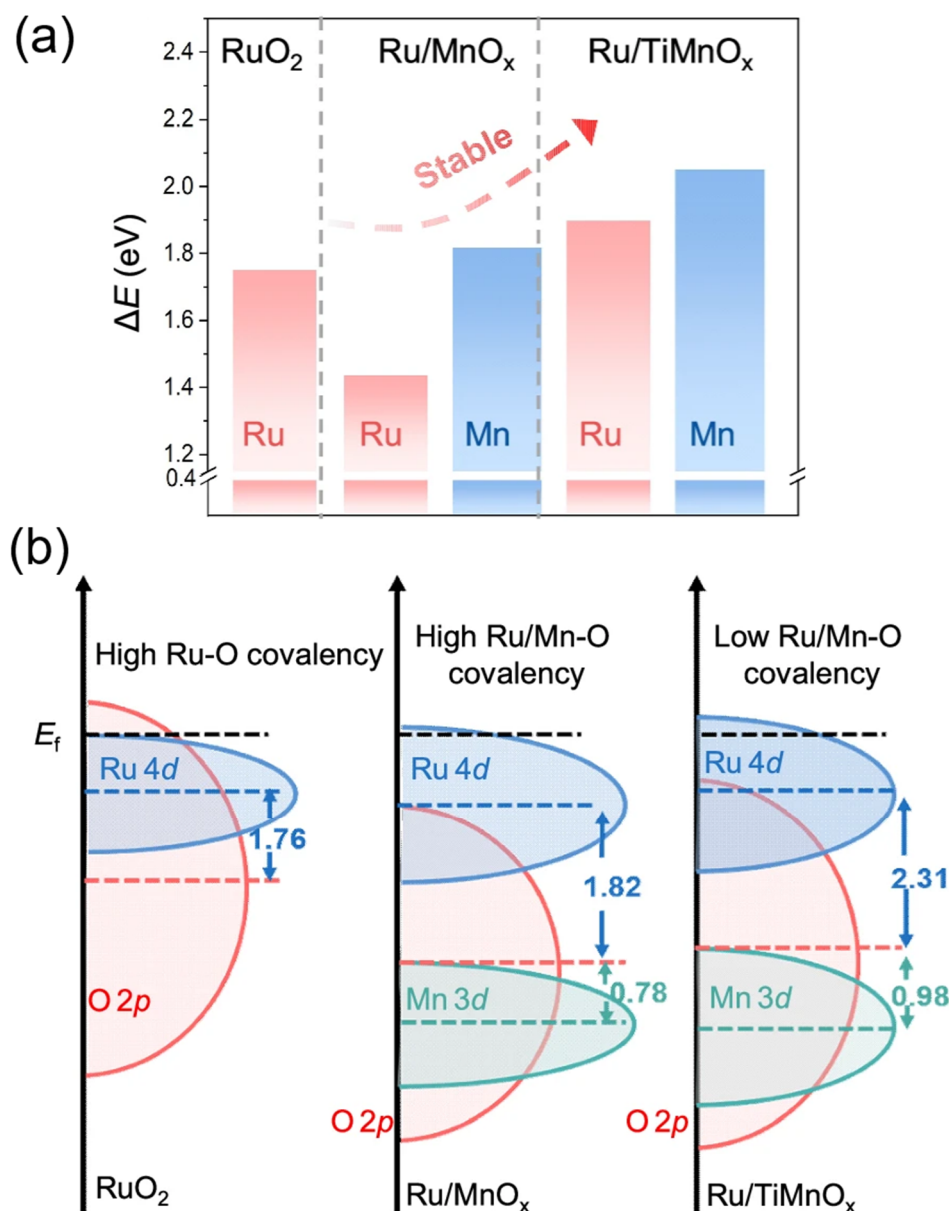


Figure 4. Electronic-structure regulation as a strategy for balancing activity and stability in RuO₂-based catalysts. (a) Stability evolution from RuO₂ to Ru/MnO_x and Ru/TiMnO_x. (b) Modulation of metal–oxygen covalency and electronic structure through Ti/Mn incorporation, which helps suppress excessive oxygen-lattice activity while maintaining catalytic performance. Reproduced from Ref. [82] under the terms of the Creative Commons Attribution 4.0 International Licence (CC BY 4.0). Copyright 2024, The Author(s).

4.3. Controlled Metastability as an Emerging Design Principle

The collective evidence discussed throughout this Perspective suggests that the activity–stability paradox of RuO₂ may not be fully resolved through rigid structural stabilization alone. Many highly active RuO₂ catalysts appear to operate within metastable surface states involving dynamic oxygen exchange, reversible reconstruction, oxidation-state evolution, and transient surface activation [53,98]. Excessive suppression of these dynamic processes may improve structural rigidity, but it may also limit some of the surface chemistry associated with rapid OER kinetics. This has led to the emerging concept of controlled metastability as a possible design principle for future acidic OER catalysts [99,100]. In this framework, the catalyst surface is expected to undergo limited and partially reversible structural evolution while remaining sufficiently stable to avoid accelerated dissolution or irreversible lattice collapse. Therefore, the goal is not maintaining a perfectly static surface, but regulating the balance between activation and degradation during operation.

Recent studies increasingly support this idea. For example, Li et al. identified a highly active RuO₅ surface state that gradually evolves during OER operation [53]. At moderate potentials, this metastable RuO₅ environment

promotes rapid oxygen evolution, whereas further evolution at higher anodic potentials leads to overoxidized RuO_4 -like species associated with catalyst deactivation. Importantly, Na incorporation helped stabilize the active RuO_5 state and enabled long-term operation exceeding 1800 h. Similarly, Zhang et al. showed that not only the concentration, but also the spatial distribution of oxygen vacancies strongly influences the balance between activity and stability in RuO_2 catalysts [101]. Their work suggested the existence of an optimal metastability window where dynamic defects remain sufficiently active for OER without triggering rapid structural degradation (Figure 5).

Other studies suggest that dynamic defect repair may help maintain catalyst stability during prolonged operation. Yan et al. anchored MoO_x clusters on RuO_2 and proposed a hydroxyl-spillover-driven oxygen-vacancy refilling mechanism. In this system, MoO_x clusters act as local hydroxyl reservoirs, promoting hydroxyl migration to oxygen vacancies generated on RuO_2 during OER. This limits excessive vacancy accumulation, suppresses Ru overoxidation and dissolution, and enables long-term acidic OER stability for over 1350 h, as well as 200 h operation in a PEM electrolyzer at 200 mA cm^{-2} [51]. More broadly, several recent stabilization strategies, including heterointerface engineering, interfacial charge redistribution, confinement effects, and support-induced electronic modulation, appear to operate by regulating rather than completely suppressing dynamic surface evolution [62,98,102,103]. This perspective also suggests that catalyst evaluation should move beyond overpotential alone. Stability metrics such as the stability number (S-number) and dissolution rates measured under realistic operating conditions provide more meaningful insight into whether a catalyst can sustain productive catalytic turnover without excessive material loss. This suggests that the most promising RuO_2 catalysts may not necessarily be the most structurally rigid systems, but rather those capable of maintaining dynamic surface evolution within a controlled and sustainable range. Ultimately, future progress in Ru-based acidic OER catalysts may depend less on eliminating dynamic surface chemistry and more on understanding how to regulate it. Controlled oxygen exchange, moderated vacancy formation, partially reversible reconstruction, and stabilized oxidation-state evolution may collectively provide a more realistic pathway toward highly active yet durable RuO_2 electrocatalysts under practical PEM water electrolysis conditions.

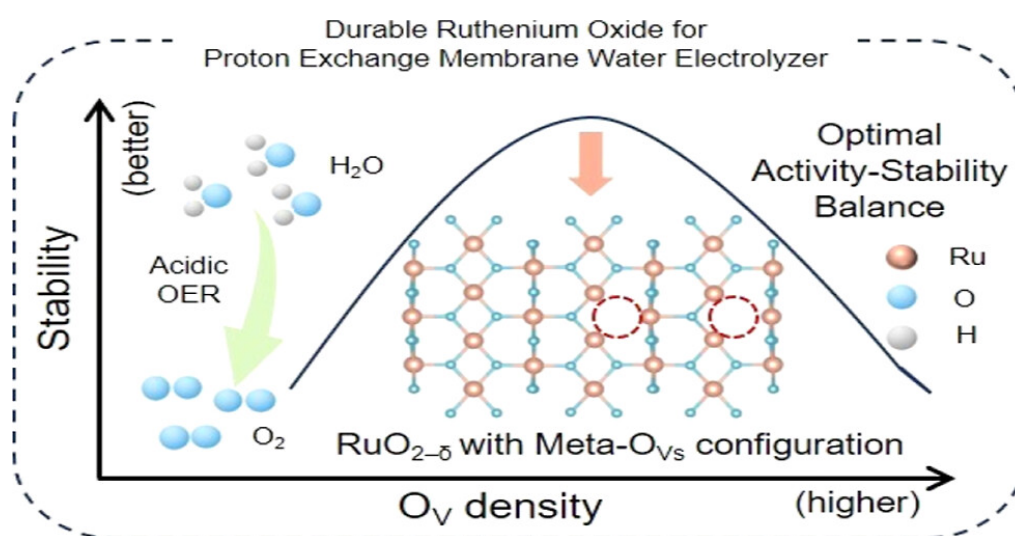


Figure 5. Conceptual illustration of the optimal activity–stability balance achieved through controlled oxygen-vacancy regulation in RuO_2 catalysts for acidic OER. Reproduced with permission from Ref. [101] with permission from the American Chemical Society. Copyright 2025, American Chemical Society.

5. Practical Implications for PEM Water Electrolysis

The stabilization strategies discussed throughout this Perspective have significantly advanced the activity and durability of RuO_2 catalysts under acidic OER conditions. As summarized in Table 1, many recently developed Ru-based catalysts have progressed beyond conventional half-cell evaluation and demonstrated stable operation in proton exchange membrane water electrolyzers (PEMWEs). Nevertheless, translating these advances into commercially viable electrolyzers remains challenging because catalyst behavior under practical operating conditions differs substantially from that observed in conventional three-electrode measurements. Most mechanistic studies are performed at relatively low current densities (typically $10\text{--}100 \text{ mA cm}^{-2}$), whereas practical PEMWE systems commonly operate at current densities approaching or exceeding $1\text{--}3 \text{ A cm}^{-2}$ and temperatures of $60\text{--}80^\circ\text{C}$. Under these conditions, the electrode/catalyst layer experiences higher oxygen evolution rates, stronger oxidative driving forces, and continuously evolving local reaction environments, all of

which place much greater demands on catalyst stability, both chemically and mechanically. Consequently, stabilization mechanisms demonstrated under laboratory conditions should ultimately be validated under realistic PEMWE operation rather than solely in model electrochemical systems [104–106].

Operation at high current densities fundamentally alters the activity–stability relationship of RuO₂ catalysts [107,108]. This increases local oxidative stress, promotes Ru oxidation-state evolution, and may intensify surface reconstruction, lattice oxygen exchange, and Ru dissolution [11,16,19,105,109–111]. At the catalyst-layer level, high current density also increases mass-transport limitations and mechanical stresses associated with water supply, oxygen bubble evolution, proton transport, and local current-density heterogeneity. Recent mechanistic studies further suggest that high anodic polarization can activate lattice oxygen, modify Ru–O bonding, and promote the evolution of metastable surface structures that may eventually trigger degradation when structural evolution becomes excessive [33,42,62,111]. Operando studies have shown that dynamically evolved RuO₅-like environments can promote rapid OER kinetics at moderate potentials, whereas further evolution at higher anodic polarization can generate less active and less stable RuO₄-like species [53]. This illustrates that activity and degradation may be intrinsically linked through potential-dependent surface evolution rather than representing fully independent processes.

Equally important is the substantial difference between laboratory-scale catalyst evaluation and practical PEMWE testing. Analyses have highlighted the limitations of directly comparing catalysts evaluated in aqueous three-electrode cells, MEAs, and full electrolyzer stacks because each environment imposes different catalyst loading, transport, ionomer, temperature, and current-density conditions [112,113]. Accordingly, catalysts showing excellent stability at 10 mA cm^{−2} do not necessarily retain comparable durability under industrially relevant PEMWE operation. For example, highly crystalline anhydrous RuO₂ recently demonstrated stable operation for more than 550 h at 1 A cm^{−2} and over 100 h at 4 A cm^{−2} after suppressing bulk proton participation and stabilizing the catalyst–ionomer interface. This demonstrates that RuO₂ stability can also be achieved through structural and interfacial regulation without heterometal doping under realistic device conditions [107]. Likewise, the representative catalysts summarized in Table 1 demonstrate that strategies based on regulating Ru–O covalency, oxygen-lattice dynamics, proton-transfer processes, or metal–support interactions can now sustain PEMWE operation at current densities ranging from several hundred mA cm^{−2} to multiple A cm^{−2}. Therefore, future benchmarking should extend beyond conventional overpotential measurements to include catalyst loading, operating temperature, current density, degradation rate, stability number (S-number), Ru dissolution, and long-term PEMWE durability using standardized testing protocols.

Beyond intrinsic catalyst chemistry, the local reaction environment within a PEMWE catalyst layer also plays an important role in determining long-term stability. Water transport, proton conduction, oxygen evolution, and local current-density distribution continuously evolve during operation, particularly near the catalyst–ionomer–electrolyte interfaces [114–118]. Consequently, Ru oxidation-state evolution, lattice oxygen activity, surface reconstruction, and dissolution are influenced not only by catalyst composition but also by the local electrochemical environment. Future catalyst design should therefore consider catalyst-layer architecture and interfacial transport phenomena together with intrinsic catalyst properties to maintain controlled surface evolution under realistic operating conditions. Additionally, the water-feeding mode may also influence RuO₂ stability. A recent semi-vapor electrolysis strategy, in which low-temperature water vapor is supplied to the anode while liquid water circulates at the cathode, enabled RuO₂ operation at high-current-density by mitigating dissolution and allowing direct use of diverse water resources. This study highlights that the activity–stability trade-off of RuO₂ can be addressed not only through catalyst design, but also by controlling the anode operating environment [119].

Finally, Ru dissolution should be considered not only as a catalyst degradation pathway but also as a potential system-level challenge because dissolved Ru species may migrate within the membrane-electrode assembly and influence long-term device durability. More broadly, the practical value of Ru-based catalysts depends not only on the lower cost of Ru relative to Ir but also on catalyst lifetime, degradation rate, catalyst loading, and replacement frequency [104,120–122]. In this regard, controlled metastability provides a useful framework for practical catalyst design by maintaining sufficient surface flexibility for rapid OER kinetics while preventing irreversible structural degradation and excessive Ru dissolution under realistic operating conditions. Ultimately, successful commercialization of RuO₂-based PEMWE anodes will require catalyst design, device engineering, and durability evaluation to be considered together rather than as independent optimization problems.

Table 1. Representative RuO₂-based acidic OER catalysts illustrating strategies for balancing activity and stability.

Catalyst	Main Design Strategy	Reported Activity	Stability/Dissolution Metric	PEMWE-Relevant Performance	Key Message	Ref.
Si–RuO ₂	Interstitial Si doping; lattice oxygen “locking”	$\eta_{10} \approx 226$ mV	800 h at 10 mA cm ^{−2} ; degradation rate ≈ 52 μ V h ^{−1}	NA	Suppressing excessive lattice oxygen oxidation can stabilize active Ru sites without fully sacrificing activity	[33]
SnRuO _x	Ru-charge regulation through Sn–O–Ru local coordination	$\eta_{10} \approx 194$ mV	26.8 mV increase over 250 h at 100 mA cm ^{−2} (107 μ V h ^{−1})	1300 h at 1 A cm ^{−2} , degradation 53 μ V h ^{−1}	Optimized Ru charge tunes Ru–O bonding, favors an AEM-dominated route, suppresses excessive lattice oxygen participation, and improves stability	[80]
Nb _{0.1} Ru _{0.9} O ₂	Monodispersed Nb incorporation; Ru–O covalency regulation; suppression of Ru overoxidation	$\eta_{10} \approx 204$ mV	360 h durability at 200 mA cm ^{−2} ; degradation rate ≈ 25 μ V h ^{−1}	100 h at 300 mA cm ^{−2}	Nb–O–Ru bonding weakens excessive Ru–O covalency, suppressing Ru overoxidation under high-current operation.	[58]
Na–RuO ₂	Stabilization of dynamically evolved RuO ₅ active state	$\eta_{10} \approx 200$ mV	>1800 h operation without obvious degradation	25 h at 500 mA cm ^{−2} , 80 h at 200 mA cm ^{−2} ,	Na stabilizes active RuO ₅ -like evolved states and suppresses overoxidation to inert RuO ₄ -like species	[53]
RuO ₂ /MoO _x	Hydroxyl-spillover-driven dynamic oxygen-vacancy refilling	$\eta_{10} \approx 195$ mV	>1350 h at 10 mA cm ^{−2} , degradation rate 81 μ V h ^{−1}	200 h at 200 mA cm ^{−2} , 80 °C with negligible degradation	Dynamic oxygen-vacancy refilling maintains controlled lattice dynamics, suppressing Ru overoxidation and irreversible structural degradation.	[51]
h-ATO/RuO ₂	Confinement of RuO ₂ in honeycomb Sb-doped SnO ₂	$\eta_{10} \approx 216$ mV	>400 h at 10 mA cm ^{−2} ; S-number 2.64×10^5 14.8× higher than unconfined RuO ₂ , degradation rate 100 μ V h ^{−1}	300 h at 500 mA cm ^{−2} and 60 °C	Confinement enriches local high-valence Ru species, suppressing net Ru dissolution and RuO ₂ overoxidation	[95]
Undoped Ru oxide anode	Crystalline, anhydrous RuO ₂ with no bulk CUS; restricts proton participation in bulk phase	$\eta_{200} \approx 150$ mV	NA	>550 h at 1 A cm ^{−2} ; degradation rate ≈ 133 μ V h ^{−1} , >100 h at 4 A cm ^{−2} with SBR binder; 3.9 A cm ^{−2} at 1.8 V	Eliminating bulk CUS and stabilizing the catalyst–ionomer interface enables durable undoped RuO ₂ anodes under practical PEMWE conditions	[107]
TS-Sr _{0.1} Ta _{0.1} Ru _{0.8} O _{2−x}	Tensile strain + Sr/Ta co-doping	H ₁₀ ≈ 166 mV	1000 h at 10 mA cm ^{−2} with 20 μ V h ^{−1} decay; 200 h at 200 mA cm ^{−2} ; order-of-magnitude higher S-number	400 h @ 500 mA cm ^{−2} with 80 μ V h ^{−1} decay	Tensile strain weakens Ru–O covalency and suppresses LOM, while Sr/Ta co-doping optimizes AEM intermediates and improves activity	[21]

Table 1. Cont.

Catalyst	Main Design Strategy	Reported Activity	Stability/Dissolution Metric	PEMWE-Relevant Performance	Key Message	Ref.
Ru/TiMnO _x integrated electrode	Chemical steam deposition; intrinsic Ru–O–Ti/Mn interactions; ML-guided composition optimization	$\eta_{10} \approx 165$ mV, Mass activity 48.5× higher than benchmark RuO ₂ in acid	3000 h at 10 mA cm ⁻² , with an average increase in overpotential of 10 μ V h ⁻¹	>180 h at 200 mA cm ⁻²	Intrinsic Ru–O–Ti/Mn interactions enable reversible redox/coordination recovery and suppress dissolution, achieving dynamic stabilization	[82]
Ru ₃ Zn _{0.85} W _{0.15} O _x	W-mediated electron accumulation in stable Ru–O–W motifs after sacrificial Zn dissolution	$\eta_{10} \approx 200$ mV	>4000 h at 10 mA cm ⁻² with no significant degradation	NA	W mediates electron accumulation from sacrificial Zn dissolution to Ru sites, increasing electron density in Ru–O–W motifs and suppressing Ru overoxidation for ultra-long stability	[77]
RuO _{1.86} F _{0.14}	F-induced hydrogen-bond-mediated deprotonation and weakened Ru–O covalency	$\eta_{10} \approx 153$ mV	>980 h; degradation rate ≈ 27 μ V h ⁻¹	1.63 V at 1 A cm ⁻² ; >100 h operation (60 °C)	Fluorine creates a hydrogen-bond-mediated proton-transfer pathway that accelerates deprotonation while reducing Ru–O covalency, suppressing overoxidation and enhancing durability.	[85]
Ru–RuO ₂ Schottky nanojunction	Metal–oxide Schottky interface; increased work function; interfacial charge redistribution	H ₁₀ ≈ 165 mV	1400 h @10 mA cm ⁻² ; S-number 6.7×10^6	1100 h @100 mA cm ⁻² ; 100 h @500 mA cm ⁻² ; 1.60 V @1 A cm ⁻²	Interfacial electronic regulation suppresses Ru overoxidation and favors OPM while maintaining high activity	[68]

CUS: coordinatively unsaturated sites; h-ATO: honeycomb-like antimony-doped tin dioxide support; SBR: styrene-butadiene rubber binder; TS: lattice tensile strain.

6. Conclusions and Outlook

RuO₂ remains one of the most promising electrocatalysts for acidic OER and is therefore central to the development of PEMWE, yet its practical deployment has been constrained by a persistent activity–stability trade-off. Throughout this Perspective, we have argued that its exceptional activity and intrinsic instability are closely linked through the same dynamic surface processes, including Ru–O covalency, lattice oxygen redox, oxidation-state evolution, surface reconstruction, and defect dynamics. Rather than viewing catalyst degradation as an independent corrosion process occurring alongside OER, increasing evidence suggests that catalytic activity and degradation are often mechanistically coupled through dynamically evolving metastable surface states. These states can promote rapid oxygen evolution, but only when their evolution remains sufficiently controlled and reversible. In this context, controlled metastability may provide a coherent framework for understanding and designing RuO₂ catalysts, where surface evolution is not eliminated but carefully regulated to maximize catalytic turnover while minimizing irreversible structural degradation.

This framework also provides a new perspective on catalyst design. The objective is not simply to maximize lattice oxygen activity, oxygen-vacancy concentration, or surface disorder, nor to completely suppress dynamic surface chemistry. Instead, future catalyst design may aim to regulate the extent, reversibility, and spatial distribution of surface evolution. Accordingly, strategies including heteroatom doping, interface engineering, support-induced electronic coupling, confinement effects, controlled defect formation, and dynamic vacancy refilling should ultimately be evaluated according to their ability to maintain beneficial surface dynamics without triggering irreversible degradation. Importantly, the challenge is not simply to choose between the AEM, LOM, and OPM but to engineer a controlled and reversible oxygen-lattice chemistry that preserves the kinetic advantages of lattice oxygen participation while avoiding excessive Ru overoxidation and structural collapse. Recent advances, including Ru–RuO₂ Schottky nanojunctions, In-doped RuO₂, hydroxyl-spillover-driven oxygen-vacancy refilling, and dynamically stabilized RuO₅-like active states, demonstrate that this balance can be achieved through rational regulation of Ru–O bonding and oxygen-lattice dynamics.

Translating controlled metastability from a conceptual framework into practical catalyst design will require closer integration of operando characterization, multiscale modeling, standardized benchmarking, and data-driven catalyst discovery. Operando techniques can play a central role in distinguishing reversible surface evolution from irreversible degradation under realistic PEMWE operating conditions. In particular, isotope-labeling experiments combined with DEMS can directly probe lattice oxygen participation, while advanced operando techniques, including XAS, Raman spectroscopy, ambient-pressure X-ray photoelectron spectroscopy (AP-XPS), and transmission electron microscopy (TEM), can monitor dynamic changes in Ru oxidation state, Ru–O bonding, local coordination, and surface reconstruction during operation. Such measurements should increasingly be performed under realistic catalyst loadings, elevated temperatures, and industrially relevant current densities to bridge the gap between fundamental mechanistic studies and practical PEMWE operation.

Future theoretical studies should similarly extend beyond static density functional theory calculations toward multiscale approaches that integrate *ab initio* molecular dynamics, microkinetic modeling, and continuum-scale simulations. Such frameworks will provide a more realistic description of how catalyst composition, local reaction environment, and transport phenomena collectively govern catalyst evolution under operating conditions. At the same time, machine learning and artificial intelligence offer exciting opportunities for accelerating catalyst discovery by identifying activity–stability descriptors, guiding dopant and interface selection, and integrating operando experimental data with computational predictions. However, future AI models should be trained not only on activity descriptors but also on durability metrics, including Ru dissolution, stability number (S-number), degradation rate, and long-term PEMWE performance.

Finally, future catalyst evaluation should move beyond conventional overpotential measurements toward standardized stability benchmarking under practically relevant operating conditions. In particular, the common practice of reporting overpotential at 10 mA cm^{−2} may not reliably predict catalyst behavior at industry-relevant current densities, where mass-transport limitations, oxygen-bubble evolution, local current-density heterogeneity, and catalyst-layer degradation become increasingly important. Comprehensive assessment should routinely include catalyst loading, operating temperature, industrial current density, Ru dissolution rate, S-number, degradation rate, structural reversibility, and long-term PEMWE durability, together with accelerated stress tests representative of intermittent renewable energy operation. Such standardized evaluation will facilitate meaningful comparison among different stabilization strategies and accelerate translation from laboratory catalyst discovery to practical electrolyzer deployment. Thus, the future challenge is no longer how to suppress dynamic surface chemistry, but how to understand, predict, and precisely regulate it. Controlled metastability therefore represents more than a catalyst-design strategy; it provides a general conceptual framework for developing next-generation

acidic OER catalysts capable of combining rapid oxygen evolution with the long-term durability required for practical proton exchange membrane water electrolysis.

Author Contributions

H.A.Y.: conceptualization, literature analysis, writing—original draft, writing—review and editing, visualization, funding acquisition. C.W.: conceptualization, literature analysis, writing—review and editing, and visualization. Both authors contributed to the development of the perspective, interpretation of the literature, and revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

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All data generated and analyzed in this study are available in this published article.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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