

Industrial-Current-Density Direct Seawater Electrolysis: Coupled Mechanisms of Activity, Selectivity, and Stability — A Literature-Constrained Multiscale Design-Space Study

1st Amirul Hakim bin Ramli
University of Malaya

Kuala Lumpur, Malaysia
AmirulHakimbinRamli@outlook.com

2nd Danial Haikal bin Roslan
National University of Malaysia

Bangi, Selangor, Malaysia
DanialHaikalbinRoslan@outlook.com

3rd Chin Chee Keong*

International Islamic University
Malaysia University
Kuala Lumpur, Malaysia
ChinCheeKeong1@outlook.com

Abstract—Why: Direct seawater electrolysis could simplify water handling in saline and offshore settings, but activity at high current is inseparable from oxygen/chlorine selectivity, halide corrosion, alkaline-earth scaling, gas transport, and system architecture. Comparisons are further distorted when raw neutral seawater, alkaline seawater, asymmetric feeds, ion-separated systems, and desalination-coupled electrolysis are treated as equivalent. How: We developed a literature-constrained phenomenological model spanning six normalized electrode descriptors: intrinsic kinetics, site exposure, chloride exclusion, passivation robustness, transport efficiency, and microenvironment control. Four representative archetypes were considered: an unprotected oxyhydroxide, an electronic heterojunction, an anion-regulated microenvironment, and a gradient-integrated electrode. With what: The evidence base comprised 38 references from 2020–2026, condition-qualified benchmarks, and explicit equations for activity, oxygen selectivity, a hypochlorite-yield proxy, and degradation. Descriptor values for the four archetypes were substituted into the equations, with uncertainty and sensitivity assessed qualitatively from their structure. What: The deterministic theoretical outputs for B1, E1, M1, and G1 respectively give overpotentials of 505.67, 439.19, 399.60, and 342.35 mV at 1.0 A cm⁻²; oxygen Faradaic efficiencies of 90.27, 93.91, 98.30, and 99.11%; and predicted 1,000 h retentions of 46.38, 70.45, 94.75, and 97.51%. G1 gives an activity–selectivity–stability score of 91.42. The equations indicate that intrinsic kinetics strongly affects activity, chloride exclusion affects selectivity, and chloride exclusion together with passivation affects stability. So what: The results are theoretical inferences derived from four representative archetypes under literature-constrained model equations; large-scale design-space scanning remains a direction for future research. Industrial-current electrodes should spatially integrate catalytic kinetics, controlled ion access, chemically robust passivation, and bubble/precipitate transport. These hypotheses require experimental validation and are not certified device specifications.

Keywords—direct seawater electrolysis, industrial current density, oxygen evolution selectivity, chloride corrosion, microenvironment engineering, multiscale electrode design

I. INTRODUCTION

Electrolysis of seawater is often framed as a catalyst problem, yet its practical difficulty arises from several

coupled interfaces. The anode must sustain oxygen evolution reaction (OER) rates while suppressing chlorine evolution reaction (CER) and broader chloride oxidation reactions (ClOR), including dissolved hypochlorite formation. The cathode raises local pH and can precipitate Mg(OH)₂ and Ca-containing deposits. Both electrodes must release gas through a concentrated, multicomponent electrolyte without losing conductive contact or exposing a corrosion-prone substrate. Reviews therefore increasingly organize the field around the joint requirements of activity, selectivity, durability, and device configuration rather than a single overpotential [1] [2] [3].

For this study, industrial current density is operationally defined as 0.5 – 1.0 A cm⁻² geometric area. This range enables consistent comparison with many recent high-rate reports, although industrial stacks may exceed 1.0 A cm⁻² and may operate at elevated temperature, pressure, electrolyte concentration, or differential pressure. A current density alone does not establish industrial relevance. Electrode area, uncompensated resistance correction, catalyst loading, gas purity, product crossover, voltage efficiency, lifetime, duty cycle, and balance-of-plant energy remain necessary context. Comparative reviews have similarly emphasized that high-rate claims should include chloride-derived products and corrosion evidence, not activity alone [4].

The phrase “direct seawater electrolysis” also hides distinct system boundaries. Raw neutral seawater means untreated or minimally filtered seawater contacting the electrode without bulk alkalization or acidification. Alkaline seawater contains added base, commonly KOH, and offers a larger thermodynamic separation between OER and chlorine chemistry while changing carbonate equilibria, conductivity, and scaling. Asymmetric feeds maintain different anolyte and catholyte compositions across an ion-conducting separator. Ion-separated membrane systems use a membrane or hydrophobic interface so that seawater supplies water but aggressive ions do not freely contact the catalyst. Desalination-coupled systems remove salts before conventional electrolysis and must be assessed at the level of delivered hydrogen, water coproducts, heat integration, and maintenance. These categories solve different problems and

Corresponding Author: Chin Chee Keong, Kuala Lumpur, Gongbak Road, 53100, Kuala Lumpur, Malaysia, ChinCheeKeong1@outlook.com

cannot be ranked by mixing half-cell overpotentials, full-cell voltages, and system energy values [5] [6] [7] [8].

The central scientific tension is that the mechanisms controlling the three performance domains are coupled but not identical. Faster intrinsic OER kinetics lowers activation loss, yet high anodic potential can create defect states, restructure precatalysts, or accelerate halide attack. Excluding chloride can suppress parasitic oxidation and corrosion, but a dense barrier can also impede hydroxide, water, electron, or bubble transport. Increasing porosity exposes sites, yet can create tortuous pockets that trap gas and precipitates. Moreover, chloride is not invariably harmful at every site: specific adsorption at Fe in NiFe layered double hydroxide (LDH) has been associated with suppressed Fe leaching and a more active high-valence Ni state under alkaline conditions [9]. The useful design question is therefore not “How can chloride be completely removed?” but “How should ion activity, catalytic reconstruction, passivation, and transport be spatially regulated?”

This work addresses that question without claiming new experimental discovery. The workflow first classifies published evidence by electrolyte and device boundary, then converts recurring mechanisms into six bounded descriptors. A transparent coupling model maps those descriptors to high-current overpotential, Tafel slope, a hypochlorite-yield proxy, oxygen Faradaic efficiency (FE), degradation, retention, and a geometric-mean activity – selectivity – stability (ASS) score. The evidence-to-design workflow is summarized in Figure 1.

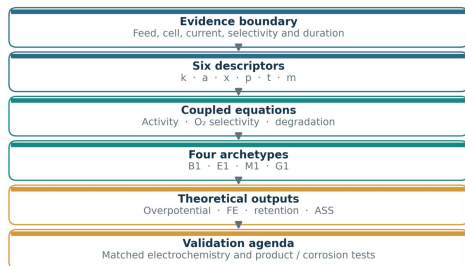


Fig. 1. Evidence-to-design workflow for the four-archetype literature-constrained study.

The mechanistic architecture evaluated by the model is summarized in Figure 2. It separates electrolyte-facing ion regulation from catalytic reconstruction, electronic passivation, current collection, and bubble/precipitate transport so that each function can be tested independently.

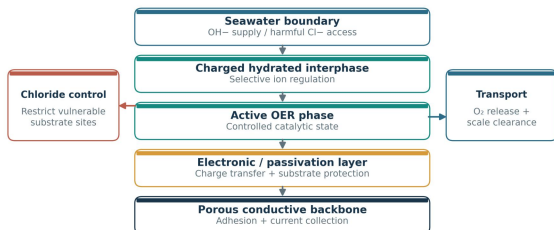


Fig. 2. Coupled activity – selectivity – stability mechanism proposed for gradient-integrated direct-seawater electrodes.

The contribution is threefold. First, it separates evidence classes and system boundaries before comparison. Second, it provides explicit equations and four representative parameter sets for a manually reproducible, mechanistically interpretable case comparison. Third, it translates the inferred trade-offs into falsifiable design rules. The model is deliberately phenomenological: it does not predict a named composition from first principles, and it does not convert literature values obtained under incompatible conditions into pooled experimental statistics. The terms and evidence classes applied throughout the analysis are defined in Table I.

TABLE I. TERMINOLOGY AND EVIDENCE CLASSES USED IN THIS MANUSCRIPT.

Term or class	Operational meaning	Included evidence	Excluded inference
Industrial current density	0.5–1.0 A cm ^{−2} geometric area in this study; stacks may exceed it	Condition-qualified high-rate electrode or cell tests	Automatic industrial readiness
Raw neutral seawater	Unalkalized, unacidified seawater contacting an electrode	Direct-contact flow or batch tests with stated source/temperature	Added-KOH tests relabeled as raw seawater
Alkaline seawater	Seawater or simulated seawater with added hydroxide	Half-cell, full-cell, or AEM tests with base concentration stated	Neutral-feed selectivity claims
Asymmetric/ion-separated	Different feeds or an interface that restricts salt contact	AEM, membrane-mediated, or purification-coupled devices	Unrestricted direct contact at both electrodes
Literature-reported benchmark	Value stated by a verified primary source	Voltage/overpotential, current, duration, FE with conditions	Cross-study significance testing
Model-derived result	Deterministic output from Section 4 equations	Four archetypes and direct equation substitutions; qualitative assumptions	New physical measurement or causal effect
Proposed validation	Prospective test with observable and failure criterion	Conventional electrochemistry, O ₂ and chlorine assays, ICP, IC, RRDE; advanced interfacial probes only as future options	Completed experiment or certified specification

II. LITERATURE REVIEW

A. Competitive anodic chemistry and selectivity measurement

OER competes with chlorine chemistry through both thermodynamic and kinetic pathways. In acidic or near-neutral chloride electrolyte, chloride can be oxidized to Cl₂, which hydrolyzes and participates in pH-dependent equilibria involving HOCl and ClO[−]. In alkaline media, the often-cited separation between OER and hypochlorite formation is approximately 480 mV, but that value is a

thermodynamic interpretation rather than a universal kinetic ceiling [10] [11]. Local concentrations, interfacial electric field, adsorption energies, catalyst oxidation state, temperature, mass transfer, and product residence time can move the observed onset and alter product distributions. “No visible chlorine” is therefore not evidence of unity oxygen FE.

Selectivity measurement is vulnerable to delayed chemistry. Gas collection can overestimate oxygen production if dissolved oxidants decompose, while an ex situ hypochlorite assay can miss a transient product. Rotating ring-disc electrode detection in simulated near-neutral seawater showed why time-resolved product analysis matters: PtRu retained 85.5% OER FE even at 1 M chloride, while increasing chloride strongly changed current at fixed potential [12]. A credible selectivity protocol should combine calibrated O₂ quantification with Cl₂/HOCl/ClO[−] analysis, define sampling time and downstream decomposition controls, and report product crossover. The absence of detected OCl[−] under one protocol, as in an asymmetric alkaline NiFe-LDH anode configuration, is valuable but remains method- and boundary-specific [13].

Interfacial chloride control follows several routes. Graphene oxide on FeOOH/Ni – Co hydroxide provided an early chloride-blocking layer in alkaline natural seawater [14]. Selective anion-gating with a Ni₃N interlayer was later proposed to preserve OH[−] access while retarding chloride access to nickel foam [15]. PF₆[−] intercalation and bias-driven adsorption stabilized Fe against segregation during ampere-level anode oxidation, although the additive-containing anolyte is not equivalent to raw seawater [16]. These approaches share a goal — lower harmful chloride activity at vulnerable sites — but differ in permeability, electronic function, chemical stability, and possible ion release.

Total exclusion is not a universal mechanistic requirement. Chloride adsorption at selected Fe sites can change the steady reconstructed surface and inhibit a dissolution route [9]. Controlled chloride proximity was also reported to promote reconstruction of NiS₂/NiFe-MOF nanosheets to dense γ -NiFeOOH with high OER selectivity [17]. The distinction is between site-specific, potential-dependent participation in forming or stabilizing an active phase and uncontrolled access to defect, substrate, or grain-boundary sites where M – Cl formation initiates corrosion. A selective electrode may thus need a spatial gradient rather than a uniformly impermeable coating.

B. Local pH, alkaline-earth scaling, and microenvironment control

Bulk pH does not describe the reaction plane at high current. OER consumes OH[−] in alkaline operation, while the cathodic hydrogen evolution reaction produces OH[−] from water. Diffusion and convection must replenish or remove these species through gas-filled pores. At the anode, OH[−] depletion can narrow the OER/ClOR selectivity advantage. At the cathode, high local pH drives Mg(OH)₂ precipitation and can promote calcium carbonate or mixed scale, depending on alkalinity and dissolved inorganic carbon. Deposits block sites, change pore wetting, and raise transport resistance.

Lewis-acid and proton-accepting interfaces seek to maintain a favorable local environment without fully alkalizing the feed. Across MnO₂, Fe₂O₃, and Cr₂O₃ layers on Co₃O₄, lower oxide pK_a correlated with stronger OH[−] enrichment and lower local chloride concentration [18]. A Cr₂O₃-modified catalyst was reported to capture OH[−] through dynamic water dissociation and enabled a raw-seawater flow electrolyser to reach 1.0 A cm^{−2} at 1.87 V at 60 °C, albeit with a 100 h-scale durability demonstration [19]. Partial alkaline corrosion of amorphous NiMoS_x similarly exposed Lewis-acid Ni²⁺ sites and vacancies proposed to replenish interfacial OH[−] in an alkaline seawater flow cell [20]. These studies establish plausible microenvironment levers, but direct local-pH and ion-activity measurements remain scarce.

A complementary strategy creates charged interphases. Sulfur-derived sulfate and chromium sites in NiS₂/Cr₂S₃ were assigned, respectively, to chloride repulsion and OH[−] enrichment during alkaline seawater oxidation [21]. The multilayer CoCH – NiBO_x – Ni(OH)₂/Ni-foam architecture reported by Tanveer ul Haq and co-workers used carbonate functionality for chloride repulsion and proton management, a NiBO_x interlayer for electronic/passivation control, and porous nanosheets for access and gas release [22]. The authors reported 408 mV at 1 A cm^{−2} in 1 M KOH + 0.5 M NaCl, approximately 420 mV at 1 A cm^{−2} in unpurified seawater, 98% oxygen FE in unpurified seawater, and 300 h at 100 mA cm^{−2} in alkaline seawater [22]. These values are source-reported, not outputs of the present model.

C. Reconstruction, passivation, and halide corrosion

Many chalcogenides, phosphides, nitrides, and metal – organic precatalysts reconstruct under anodic bias. Reconstruction can be productive when it creates a conductive, adherent oxyhydroxide with controlled defect density. It can be destructive when dissolution, redox cycling, or volume change opens paths to the substrate. A MoO₃ confinement layer on CoO was reported to restrict reconstruction toward a stable Co – Mo double-hydroxide interface [23]. By contrast, an ultrathin TiO_x layer on FeNiP was reported to stabilize the anion lattice and permit reconstruction-free OER, with ordered Ir sites favoring an oxide-path mechanism [24]. These are different design hypotheses; “more reconstruction” and “no reconstruction” cannot both be generalized without specifying composition and operating state.

Passivation must remain electronically and ionically functional. Phosphate formation in Fe,P-doped NiSe₂ and molybdate formation on RuMoNi illustrate in situ protective layers that retain high-rate activity [25] [26]. Oxygen vacancies complicate this picture. In one mechanism, OER-generated vacancies were identified as preferred chloride-adsorption sites that initiate M – Cl corrosion; VO₄^{3−} modification and hydrogen-bond stabilization of OH[−] were used to block that cycle [27]. A compact NiFe-LDH layer on nickel foam instead retarded chloride access and supported a proposed dynamic Fe-leaching/redeposition equilibrium [28]. The desired state is therefore not an inert film but a controlled steady state of charge transfer, reactant access, defect generation, and repair.

Natural seawater adds bromide and other species that simple NaCl tests omit. Chloride was reported to produce narrow, deep pits in Ni-based anodes, whereas bromide produced broader shallow etching and catalyst-layer spalling [29]. Long-term testing should consequently quantify both halides, dissolved metals, layer adhesion, and substrate exposure. Continuous chronopotentiometry alone cannot separate catalyst deactivation from contact loss, membrane contamination, changing solution composition, or bubble blockage.

D. Gas transport and precipitation are electrode-scale mechanisms

At 0.5 – 1.0 A cm⁻², gas volume and bubble coverage are not secondary. Bubbles mask active area, lengthen ionic paths, alter local current distribution, and mechanically disturb deposits. Periodic three-dimensional nickel structures reduced bubble coalescence, jamming, and trapping relative to stochastic foam in alkaline water, providing a physical transport control rather than direct seawater selectivity evidence [30]. A superhydrophilic, underwater-superaerophobic full electrode assembly sustained high-rate alkaline-water operation and showed that the current collector and interface matter alongside catalyst wettability [31].

Seawater introduces coupling between gas and solids. Honeycomb cathodes enabled broadly released H₂ bubbles to displace Mg/Ca-derived precipitates, sustaining alkaline seawater reduction for 1,000 h and a natural-seawater flow cell for 150 h at 500 mA cm⁻² [32]. Self-supported Ni₃S₂/Co₃S₄ nanosheet arrays also provided an early porous-electrode benchmark at 800 mA cm⁻² in alkaline natural seawater, although the study did not independently measure bubble-release kinetics [33]. Thus, morphology can improve effective activity and stability without changing the elementary OER pathway or intrinsic chlorine selectivity.

E. System boundary changes the meaning of “direct”

Separating seawater from the catalytic environment can remove several constraints at once. A hydrophobic membrane-mediated electrolyser operated for more than 3,200 h at 250 mA cm⁻² by drawing water across an interface while restricting ions [5]. Online flow-electrode capacitive deionization achieved 98.47% desalting at 1.6 V before alkaline electrolysis and supported a reported 100 h at 500 mA cm⁻² [6]. An offshore platform coupled in situ purification with electrolysis under wave and wind fluctuations, producing hydrogen for more than 240 h at 250 mA cm⁻² [34]. These are seawater-to-hydrogen systems, but they do not establish that raw seawater can contact both electrodes indefinitely.

Desalination-coupled electrolysis remains an important comparator. Reverse osmosis (RO) energy for the water consumed per kilogram of hydrogen is small relative to electrolysis under standard assumptions; one analysis estimated electrolysis energy to exceed the associated RO requirement by approximately 1,350 – 2,847 times and desalination to add at most 1% to hydrogen price [8]. A separate SWRO – PEM scenario found additions below US\$0.1 kg⁻¹ H₂ and 0.1% emissions under its assumptions [35]. Conversely, low-temperature distillation driven by electrolyser waste heat can co-produce hydrogen and fresh water, as demonstrated in 20 and 250 kW systems [7]. Direct

electrolysis must therefore earn its system advantage through location, heat and water integration, maintenance, footprint, or resilience — not merely avoidance of a small nominal desalination energy term.

III. RELATED WORK

Recent primary studies can be grouped by the architectural constraint they address. Chloride-blocking outer layers demonstrated that selectivity and substrate protection could be engineered at an interface [14]. Asymmetric alkaline feeds preserved a favorable NiFe-LDH anode environment and enabled direct measurement of high oxygen selectivity [13]. Dual-doped NiSe₂ linked active-site chemistry to an in situ passivation layer [25]. NiFe-LDH studies then showed both anomalous beneficial chloride adsorption [9] and dense-layer protection with dynamic Fe behavior [28]. Carbonate interlayers and graphene quantum dots sustained approximately 1.25 A cm⁻² for more than 2,800 h [36], while Os – Ni₄Mo/MoO₂ micropillars combined strong metal – support interaction, transport, and dual chloride-repelling layers [37]. Later work used controlled chloride exposure to drive dense γ -NiFeOOH reconstruction [17], blocked vacancy-mediated M – Cl chemistry with vanadate [27], and restricted reconstruction with MoO₃ [23]. These examples demonstrate rapid progress but also show that nominally similar “chloride-resistant” labels encompass different mechanisms and test boundaries. The condition-qualified literature comparison is provided in Table II.

TABLE II. CONDITION-QUALIFIED COMPARISON OF REPRESENTATIVE PRIMARY STUDIES. VALUES ARE LITERATURE-REPORTED AND ARE NOT NORMALIZED OR POOLED.

Study	Regime and cell basis	Electrolyte/fe ed	Current and electrical metric	Dur at ion	Selectivity evidence
Jadhav et al. [14]	Two-electrode overall cell	Alkaline natural seawater	1.0 A cm ⁻² at 2.02 V	>378 h at 1.0 A cm ⁻²	Chloride-blocking design; retain source protocol
Drescher et al. [13]	Asymmetric AEM full cell	Saline catholyte; 0.5 M KOH anolyte	O ₂ FE ~94% at 0.8 A cm ⁻²	~100 h at 0.2 A cm ⁻²	No detected OCl ⁻ ; stepped O ₂ FE near 100%
Chang et al. [25]	Bifunctional overall cell	Condition-specific seawater electrolyte	0.8 A cm ⁻² at 1.8 V	>200 h	P–O passivation proposed; product method required for comparison
Fan et al. [36]	High-rate seawater electrolysis	Seawater, architecture-specific conditioning	~1.25 A cm ⁻²	>2,800 h	Chloride adsorption/corrosion suppressed; no inferred chlorine FE
Liu et al. [37]	Separate HER/OER half-reactions	South China Sea water + 1 M KOH	OER η = 336 mV at 0.5 A cm ⁻²	2,500 h; 0.37 μ V h ⁻¹ OER degradation	Dual chloride-repelling layers; not a full-cell voltage
Du et al.	Anode half-cell	Natural seawater + 1	Anode η = 220	>9,000 h	Dense interlayer;

[28]	and AEM full cell	M KOH	mV; cell 1.91 V at 1.0 A cm ⁻²	anode; >700 h cell	half-cell/cell lifetimes separate
Tang et al. [17]	Anode oxidation	Natural seawater + 1 M KOH	$\eta = 213$ mV at 0.5 A cm ⁻²	>7,000 h at 1.0 A cm ⁻²	99% OER FE; negligible ClO ⁻ reported
Guo et al. [19]	Raw-seawater flow full cell	Unalkalized/unacidified real seawater, 60 °C	1.0 A cm ⁻² at 1.87 V	>100 h at 0.5 A cm ⁻²	Local alkalinity and reduced precipitation claimed
Zhou et al. [23]	Anode and direct-seawater flow cell	Direct seawater; source conditions	Cell 1.0 A cm ⁻² at 1.93 V	1,000 h anode at 0.6 A cm ⁻² ; 500 h cell	100% anode FE; >95% cell FE reported
Kang et al. [26]	Anode and AEM device	Alkaline seawater	Cell 1.0 A cm ⁻² at 1.72 V	>3,000 h anode at 0.5 A cm ⁻²	Molybdate repulsion; 77.9% source-defined efficiency
Tanveer ul Haq et al. [22]	Anode and overall cell	1 M KOH + 0.5 M NaCl; unpurified seawater	$\eta = 408\text{--}420$ mV and cell 1.65 V at 1.0 A cm ⁻²	300 h at 0.1 A cm ⁻² in alkaline seawater	98% O ₂ FE in unpurified seawater; no hypochlorite reported

At the device level, three strategies deserve separate treatment. Membrane-mediated water extraction isolates electrodes from salts [5]. Asymmetric and AEM devices maintain engineered anolytes while accepting saline water elsewhere [13] [15]. Pretreatment or purification systems alter the feed before reaction [6] [34]. Each can outperform unrestricted direct contact in durability because it has changed the chemical problem. They should be compared using total voltage, auxiliary energy, water recovery, membrane life, product purity, and maintenance, not placed in the same catalyst-overpotential league table.

The present study differs from prior reviews and material reports in purpose. Reviews synthesize mechanism and device categories [1] [10] [2] [11], whereas primary studies optimize named compositions under specific conditions. Here, verified mechanisms are converted into six explicit descriptors and considered through coupled equations for four representative electrode archetypes. The contribution is an auditable mapping from literature mechanisms to architecture-level trade-offs and prospective validation criteria. The source-reported multilayer result [22] informs architectural plausibility but does not validate the theoretical gradient archetype.

IV. METHODOLOGY

A. Evidence constraints and research workflow

The evidence set contains 37 verified 2020 – 2026 sources plus the supplied 2025 Small article as reference [22]. Primary values were extracted only with their reported test boundary. Reviews supported terminology and mechanism framing, not reassigned experimental values. Analytical system studies supported boundary comparisons, not plant

measurements. The seven diagrams and conceptual comparisons were developed for this study and do not reproduce source figures.

Six dimensionless descriptors, each bounded on [0,1], represent the design space. Intrinsic kinetics (k) encodes the capacity of the active phase to sustain OER charge transfer. Site exposure (a) represents accessible catalytic area without asserting a particular roughness factor. Chloride exclusion (x) represents reduced harmful chloride activity at vulnerable interfaces. Passivation robustness (p) represents chemical and mechanical persistence of a protective interphase. Transport efficiency (t) represents ion delivery, bubble release, and avoidance of stagnant pores. Microenvironment control (m) represents local OH⁻ retention, proton management, and favorable ionic organization. These are modeling coordinates, not directly measured universal material constants.

B. Deterministic coupling equations

For each of the four archetypes, the coupling bonus was defined as $C = 35 \sqrt{k m t}$, with the product clipped to [0,1] before the square root. A chloride penalty was $P_{Cl} = 35(1 - x)(1 - m)$. The modeled OER overpotential at 1.0 A cm⁻², in mV, was:

$$\eta_{a,1000} = \text{clip}[610 - 115k - 58a - 52t - 40m - C + P_{Cl}, 285, 560] \quad (1)$$

The Tafel slope, in mV dec⁻¹, was:

$$b = \text{clip}[128 - 57k - 19m - 11t + 8(1 - a), 34, 130] \quad (2)$$

The hypochlorite-yield proxy, expressed as percent, was:

$$Y_{OCl} = \text{clip}[7.8(1 - x)^{1.55}(1 - 0.55m) \exp(0.28(\eta_{a,1000} - 400)/100, 0.05, 12] \quad (3)$$

This quantity is a phenomenological penalty, not an analytical prediction of a specific assay. Oxygen FE was:

$$FE_{O_2} = \text{clip}[99.45 - Y_{OCl} - 1.5(1 - t) - 0.75(1 - p), 84, 99.4] \quad (4)$$

The degradation constant in h⁻¹ was:

$$k_{deg} = 2.2 \times 10^{-5} + 7.4 \times 10^{-4}(1 - x)^{1.35}(1 - p)^{1.10}[1 + 0.62(1 - t)] \exp(0.18(\eta_{a,1000} - 400)/100) \quad (5)$$

Predicted activity retention was exponential: $R_{300} = 100 \exp(-300k_{deg})$ and $R_{1000} = 100 \exp(-1000k_{deg})$. The auxiliary 300 h potential-drift proxy was $D_{300} = 10 + 310(1 - R_{300}/100) + 18(1 - t) \text{ mV}$. Charge-transfer resistance and bubble-coverage proxies were $R_{ct} = \text{clip}[47 - 21k - 11t - 8m - 4a, 4, 48] \Omega$ and $\theta_b = 0.31(1 - t)^{1.2} + 0.035$.

Three normalized performance indices were calculated. The activity index was $I_A = \text{clip}[(560 - \eta_{a,1000})/275, 0, 1]$.

The selectivity index was $I_{sel} = \text{clip}[(\text{FE}_O/100)(1 - Y_{OCl}/100), 0, 1]$. The stability index was $I_{stab} = \text{clip}[R_1/1000, 0, 1]$. The composite score was the geometric mean, $ASS = 100(I_A I_{sel} I_{stab})^{1/3}$. The geometric rather than arithmetic mean penalizes a design that performs poorly in any one domain.

C. Sampling, archetypes, uncertainty, and sensitivity

Four representative architectures were selected to compare plausible combinations of the six descriptors under the same literature-constrained equations. Their parameters were inserted directly into the expressions above; no automated sampling of a broad design space was performed. The comparison is a finite theoretical case study rather than an exhaustive search or an optimization result.

Four architecture archetypes were specified before evaluation. B1, the unprotected oxyhydroxide, used $[k, a, x, p, t, m] = [0.55, 0.52, 0.12, 0.25, 0.42, 0.18]$. E1, the electronic heterojunction, used $[0.78, 0.64, 0.24, 0.48, 0.63, 0.35]$. M1, the anion-regulated microenvironment, used $[0.72, 0.69, 0.78, 0.69, 0.66, 0.82]$. G1, the gradient-integrated electrode, used $[0.91, 0.86, 0.88, 0.90, 0.91, 0.90]$. Their six descriptor inputs and deterministic outputs are reported in Table III.

Only a single deterministic result is reported for each archetype. Descriptor assignments and coefficients are interpretive assumptions, so the apparent precision of calculated values should not be mistaken for experimental uncertainty. The direction of possible bias is considered qualitatively: correlated changes in exclusion and transport, or in passivation and resistance, may reduce the apparent advantage of integrated designs. No perturbation-derived confidence or percentile intervals are claimed.

Qualitative sensitivity follows directly from the signs, magnitudes, and interactions of the stated equations. The activity expression weights k and includes a $k - m - t$ coupling term; the hypochlorite proxy decreases nonlinearly with x and depends on m ; and the degradation expression couples x , p , and t . These mathematical tendencies are hypotheses for matched electrochemical testing, not measured causal effects or surrogate-model feature importances. No inferential p -values are assigned to four deterministic theoretical cases.

V. DATA

The quantitative model inputs consist of the six descriptor values for B1, E1, M1, and G1 in Table III. The equations in Section 4 and the four rows of Table III supply the information needed to reproduce each theoretical case by direct substitution. Literature benchmarks in Table II remain separate source-reported observations. A larger design-space scan, if warranted by experimental calibration, remains future work.

The data classes are intentionally not merged. Literature benchmarks in Table II retain source conditions and are not treated as outputs of the model. The four archetypes are conceptual combinations of mechanisms, not synthesized electrodes or fitted replicas of individual studies. This separation prevents circular validation in which equations inspired by published trends are claimed to reproduce those publications quantitatively.

VI. RESULTS

A. Architecture comparison

The four deterministic archetypes illustrate progressively integrated functions, as summarized in Figure 3.

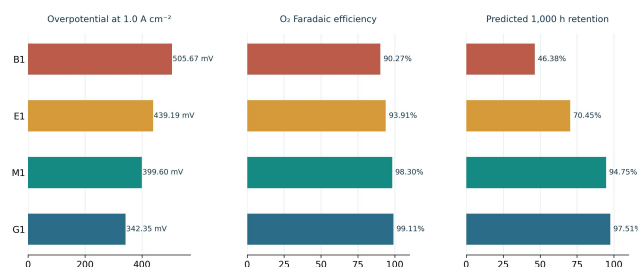


Fig. 3. Model-derived comparison of four electrode architecture archetypes. Values are deterministic theoretical outputs, not experimental measurements.

B1 required 505.67 mV, gave 90.27% O₂ FE, retained 46.38% at 1,000 h, and scored 42.42. Improving electronic function and transport in E1 lowered overpotential to 439.19 mV, increased FE to 93.91%, raised retention to 70.45%, and produced ASS 65.21. M1 gained most strongly in selectivity and durability: 399.60 mV, 98.30% FE, 94.75% retention, and ASS 81.48. G1 combined high descriptor values and gave 342.35 mV, a 50.14 mV dec⁻¹ Tafel slope, 99.11% FE, 0.125% hypochlorite proxy, 97.51% retention, 7.24 Ω charge-transfer resistance, and ASS 91.42.

TABLE III. DESCRIPTOR VALUES AND DETERMINISTIC OUTPUTS FOR THE FOUR ARCHITECTURE ARCHETYPES.

ID and architecture (theoretical archetype)	Descript or vector $k/a/x/p/t/m$	Model ed η at 1.0 A cm ⁻² ; Tafel slope	Model ed O ₂ FE; OCl ⁻ proxy	Predict ed retenti on at 1,000 h	Rct	AS S
B1 unprotected oxyhydroxide	0.55 / 0.52 / 0.12 / 0.25 / 0.42 / 0.18	505.67 mV; 92.45 mV dec ⁻¹	90.27 %; 7.749 %	46.38%	27.31 Ω	42.42
E1 electronic heterojunction	0.78 / 0.64 / 0.24 / 0.48 / 0.63 / 0.35	439.19 mV; 72.84 mV dec ⁻¹	93.91 %; 4.594 %	70.45%	18.33 Ω	65.21
M1 anion-regulated microenvironment	0.72 / 0.69 / 0.78 / 0.69 / 0.66 / 0.82	399.60 mV; 66.60 mV dec ⁻¹	98.30 %; 0.409 %	94.75%	15.30 Ω	81.48
G1 gradient-integrated electrode	0.91 / 0.86 / 0.88 / 0.90 / 0.91 / 0.90	342.35 mV; 50.14 mV dec ⁻¹	99.11 %; 0.125 %	97.51%	7.24 Ω	91.42

The case ordering is conditional on the chosen descriptor values and model coefficients. B1 combines weak chloride exclusion and passivation, whereas E1 improves intrinsic kinetics and transport; M1 adds stronger ion regulation and microenvironment control; and G1 combines these with robust passivation. If a real coating improves exclusion while

substantially restricting hydroxide access, G1's modeled activity advantage could diminish. Likewise, passivation failure or bubble blockage could lower predicted retention. These possibilities define experimental checks rather than statistical uncertainty intervals.

B. Design-space distribution and Pareto structure

The four archetypes span 342.35 – 505.67 mV in modeled overpotential, 90.27 – 99.11% in calculated O₂ FE, and 46.38 – 97.51% in predicted 1,000 h retention. These ranges merely describe four chosen theoretical inputs, not the distribution of real electrodes or an estimated population. The contrast between B1 and G1 illustrates the model's assumed coupled benefit from kinetics, chloride regulation, passivation, and transport.

The finite comparison of activity, selectivity, and stability is shown in Figure 4.

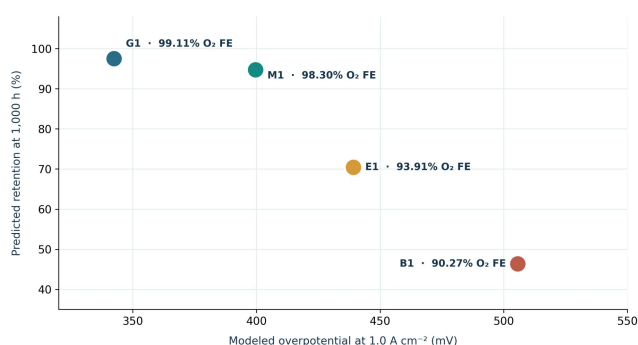


Fig. 4. Conceptual activity – stability comparison of B1, E1, M1, and G1, annotated by modeled oxygen selectivity. Four prescribed cases only; no sampled Pareto set.

Within the four prescribed input combinations, G1 has the highest calculated ASS score (91.42), the lowest overpotential (342.35 mV), the highest O₂ FE (99.11%), and the greatest predicted retention (97.51%). Thus these four cases do not demonstrate a non-dominated frontier or an optimized material. Rather, comparing B1, E1, and M1 clarifies the model assumption that improvement in one function alone need not resolve chlorine chemistry or long-term corrosion. Other untested descriptor combinations could alter the ordering.

C. Response surfaces and global model sensitivity

At fixed $k = 0.78$, $a = 0.72$, $t = 0.75$, and $m = 0.78$, Figure 5 schematically illustrates how the equations assign different roles to chloride exclusion and passivation robustness. It is a conceptual comparison of limiting tendencies, not a sampled numerical response surface.

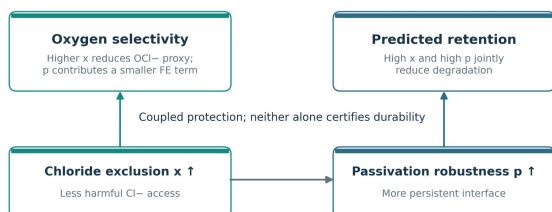


Fig. 5. Conceptual interaction of chloride exclusion and passivation robustness in oxygen selectivity and predicted 1,000 h retention, based on the stated equations.

O₂ FE changed mainly along the chloride-exclusion axis because the hypochlorite proxy depends directly and nonlinearly on $(1 - x)^{1.55}$; passivation adds a smaller FE penalty. Retention required both chloride exclusion and passivation because they multiply in k_{deg} . A high value of either descriptor could compensate partly for a weak value of the other, but the upper-right region was most robust. This mathematical interaction represents a physically testable hypothesis: reducing chloride access will not ensure durability if the protective phase fractures, dissolves, or becomes electronically resistive.

The equation-level dependencies in Figure 6 identify qualitative priorities for testing across the four archetypes.

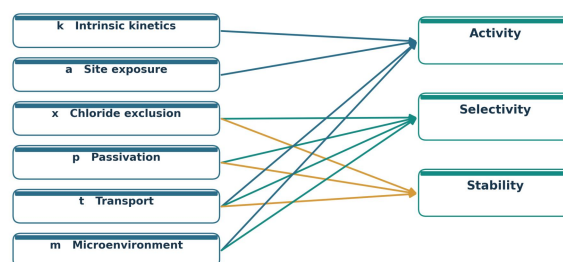


Fig. 6. Qualitative descriptor influences implied by the activity, selectivity, and degradation equations; arrows do not represent fitted feature importance.

For activity, the negative coefficient on k and the $k - m - t$ coupling favor intrinsic kinetics, while a , t , and m also affect modeled overpotential. For selectivity, the nonlinear $(1 - x)^{1.55}$ term makes harmful chloride exclusion influential within the assumed proxy, with additional roles for m , t , and p . For stability, x and p appear multiplicatively in k_{deg} and t modifies the penalty. These statements describe equation structure and the four illustrative substitutions, not global rankings from sampled inputs, surrogate fidelity statistics, or experimental causal effects.

D. Modeled polarization

The Tafel expressions in Figure 7 illustrate the four archetypes using each case's modeled η_{1000} and slope as a limited theoretical comparison of current-dependent activity.

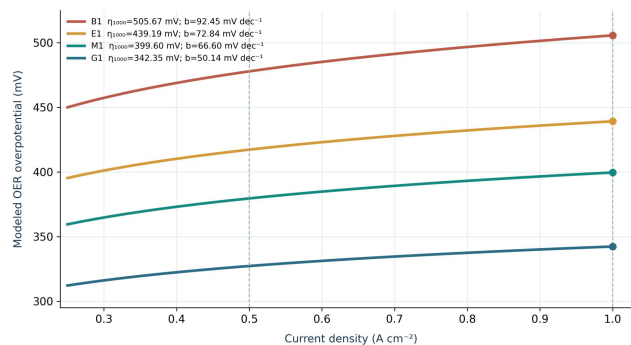


Fig. 7. Conceptual Tafel-based polarization comparison for B1, E1, M1, and G1, anchored at their deterministic 1.0 A cm⁻² overpotentials. These are not measured polarization curves.

For each architecture, $j = 1000 \times 10^{\wedge}[(\eta - \eta_{1000})/b]$ mA cm⁻² is an illustrative Tafel relationship. G1 reaches the 0.5 and 1.0 A cm⁻² guide levels at lower modeled overpotential because it combines a lower anchor value and smaller slope. The diagram does not use sampled data or fitted measurements and excludes ohmic, concentration, temperature, and two-phase-flow losses that would shape a full-cell curve.

VII. DISCUSSION

A. A gradient architecture reconciles mechanisms that appear contradictory

The model's main implication is architectural rather than compositional. The literature supports several locally valid mechanisms: chloride should be repelled from corrosion-prone substrate and defect sites [14] [27]; selected chloride adsorption can stabilize or direct an active phase [9] [17]; OH⁻ should remain available near OER sites [18] [19]; a passivation layer should stabilize high-valence states without blocking charge transfer [26] [22]; and pores should clear both gas and solids [32] [30]. A single homogeneous layer is unlikely to optimize all functions.

As illustrated in Figure 2, a conductive porous backbone first provides low-resistance current collection and adhesion. An electronic/passivation interlayer then limits substrate oxidation and stabilizes the active phase. A reconstructable outer catalyst supplies OER sites, while proton-accepting or Lewis-acid functions maintain local alkalinity. A charged, hydrated anionic boundary lowers harmful chloride activity without sealing water and hydroxide transport. Finally, graded hydrophilic – aerophobic pores release O₂ and displace scale. The layers need not be compositionally discrete, but each function should be experimentally separable.

This interpretation explains the modeled transition from E1 to M1. E1 improves kinetics, site exposure, and transport, reducing overpotential, but weak chloride regulation limits FE and retention. M1 has slightly lower intrinsic kinetics than E1 yet performs better overall because microenvironment and exclusion suppress the nonlinear selectivity and degradation penalties. G1 adds robust passivation and transport, raising all three indices. The geometric ASS score rewards this balance; it should not replace the underlying outputs or imply that 1 ASS unit has a universal engineering value.

B. Selectivity requires coupled product and corrosion accounting

A near-unity O₂ FE at one time point cannot establish long-term chloride resistance. Chlorine-derived products may be transient, dissolve, cross a membrane, react with catalyst/support, or decompose. Corrosion current can also be small relative to 1 A cm⁻² yet remove enough material over thousands of hours to cause failure. A useful validation should therefore close at least three balances: gas production, dissolved/aqueous oxidants, and material release. RRDE or rapid downstream detection can resolve transient ClOR [12], while inductively coupled plasma analysis and ion chromatography can connect product selectivity to dissolution.

The modeled hypochlorite term makes chloride exclusion influential for selectivity under the assumed equations. This

should not be interpreted as a quantitative causal attribution in real catalysts. Intrinsic adsorption energetics, an oxide-path OER mechanism, local pH, and product residence time may each change experimental selectivity. A practical initial test would compare O₂ FE and chlorine products at matched current and feed; more demanding measurements of interfacial chloride activity could be pursued subsequently.

C. Stability is a coupled chemical – mechanical – transport property

The stability surface highlights a failure mode in barrier-centric designs. Even excellent electrostatic repulsion will not preserve activity if a film delaminates under bubble stress, transforms to an insulating phase, or develops pinholes. Conversely, a robust passivation layer exposed to high chloride activity can suffer localized attack. This interaction accords with observations of deep chloride pits and broad bromide-induced spalling [29], restricted reconstruction [23], and selective-anion protection [15].

Cathodic scaling must be part of the same system test. Raw seawater can remain chemically benign at an anode yet fail through cathode blockage, diaphragm fouling, or recirculation-line deposition. Bubble-enabled precipitate removal [32] is promising because it uses the reaction product as a transport mechanism, but pore geometry must be assessed at scale. A centimeter-scale coupon may clear deposits while a large cell develops maldistribution and low-flow zones.

Intermittent operation adds another stability axis. A phosphate-passivated system endured 10,000 h of fluctuating alkaline-seawater operation at 0.5 A cm⁻² with a reported voltage increase of 0.5% khr⁻¹ [38]. That result should not be directly ranked against continuous anode-only tests; it instead shows that open-circuit and reversal states can require different protection chemistry. Future studies should report start – stop count, ramp rate, idle electrolyte, polarity events, and recovery protocol.

D. Model thresholds become falsifiable hypotheses, not specifications

The descriptor model cannot directly prescribe a composition because k , x , p , t , and m are latent constructs. Nevertheless, its tendencies can be translated into accessible observables. Chloride regulation can first be assessed through calibrated O₂ and chlorine-product assays, ion chromatography, and post-test corrosion inspection. Passivation can be examined by potential cycling, impedance, dissolved-metal analysis by ICP, and post-test adhesion; transport can be assessed by optical bubble observation, pressure drop, and deposit mass. Operando vibrational spectroscopy, isotope/ion tracers, microelectrode sampling, and cross-sectional ion mapping are possible future investigations, not methods used in this study or prerequisites for the initial validation. The corresponding prospective design rules and test boundaries are summarized in Table IV.

TABLE IV. FALSIFIABLE DESIGN RULES DERIVED FROM THE MODEL. THRESHOLDS ARE HYPOTHESES FOR VALIDATION, NOT CERTIFIED SPECIFICATIONS.

Design rule	Observable	Hypothesis threshold	Test boundary	Failure interpretation
Preserve high	Simultaneous O ₂ FE	O ₂ FE ≥98%;	Raw and	Exclusion/microenvironment inadequate

OER selectivity at 1.0 A cm ⁻²	and Cl ₂ /HOCl/CIO ⁻ balance	total chlorine products ≤0.5% charge	alkaline seawater, matched flow and temperature	or assay incomplete
Protect the substrate without sealing OH ⁻ transport	Three-electrode impedance; post-test optical inspection and dissolved-metal assay	R _{ct} rise ≤20% over 300 h; no visible penetrating defects	Geometric 0.5–1.0 A cm ⁻²	Barrier is resistive, porous to halide, or mechanically damaged
Maintain controlled local alkalinity	Bulk pH, calibrated inlet/outlet chemistry, and product selectivity; local profiling in future work	Stable bulk chemistry and O ₂ FE under defined flow; local pH target for future tests	Fixed flow, gas rate, buffering, and current	OH ⁻ delivery/proton management is insufficient
Resist chemical and mechanical degradation	Dissolved metal, thickness, adhesion, voltage drift	Retention ≥90% at 1,000 h; metal release trend non-accelerating	Continuous and intermittent protocols	Passivation dissolves, reconstructs destructively, delaminates or
Clear bubbles and alkaline-earth scale	Optical bubble observation; post-test deposit mass and active-area inspection	No persistent gas blanket; deposit coverage ≤10% active area	Raw seawater cathode at ≥0.5 A cm ⁻²	Pore/wetting design causes stagnation or scale trapping
Demonstrate system rather than coupon benefit	Delivered-H ₂ electricity, purity, water handling, maintenance	Advantage relative to stated RO/electrolysis comparator	Identical H ₂ delivery pressure and purity	Benefit lies outside chosen boundary or is offset by auxiliaries

The numerical thresholds in Table IV are deliberately challenging and provisional. They are chosen to make the architecture falsifiable, not to certify industrial service. A material that misses one threshold may still be valuable under an ion-separated architecture, and a material that passes a coupon test may fail at stack scale.

E. System selection should precede catalyst optimization

Raw neutral seawater offers the strongest simplification claim but imposes the hardest coupled chemistry. Alkaline seawater improves conductivity and anode selectivity while requiring chemical addition and scale management. Asymmetric feeds and AEM systems protect the anode environment at the cost of membranes, crossover control, and electrolyte management. Membrane-mediated water extraction can nearly eliminate direct salt contact but shifts risk to interface wetting and membrane life [5]. Desalination-coupled systems use mature separation and may exploit waste heat [7].

Accordingly, the preferred architecture depends on location and service. Offshore or remote operation may value compact in situ purification and reduced freshwater logistics [34]. Grid-connected coastal plants may favor SWRO because its energy and cost contributions are small relative to electrolysis under common assumptions [8] [35]. A catalyst result cannot settle this systems choice. The correct order is to define feed, product, duty cycle, maintenance access, and water/heat boundary, then optimize the electrode for that regime.

F. Limitations

The model is structurally transparent but intentionally simplified. Four independently assigned descriptor sets ignore synthesis correlations: stronger exclusion may reduce transport, greater site exposure may weaken adhesion, and robust passivation may increase resistance. The equations do not resolve potential-dependent adsorption, chloride speciation, carbonate buffering, bromide kinetics, temperature, pressure, salinity variation, hydrodynamics, membrane crossover, or spatial current distribution. Exponential retention assumes a constant degradation rate and therefore cannot represent induction periods, self-healing, abrupt delamination, or accelerating corrosion.

The descriptor assignments and coefficients are literature-constrained judgments, not parameters fitted to a harmonized experimental database. Published values differ in iR correction, area definition, catalyst loading, reference-electrode calibration, electrolyte preparation, flow, temperature, and product assay. The four theoretical outputs therefore cannot be validated by visual agreement with scattered literature ranges. Without calibrated measurements, numerical uncertainty bounds or a global importance ranking would imply more precision than the available evidence supports.

Finally, oxygen FE and the hypochlorite proxy are not a complete chlorine balance. Chlorate, perchlorate, adsorbed chlorine species, volatile Cl₂, and reactions with cell components may matter. The model also treats transport as one descriptor, whereas bubble removal, ion conduction, precipitation, and convective refresh can oppose each other. These limitations define the validation agenda rather than undermine the value of a transparent hypothesis generator.

VIII. CONCLUSION

This study establishes a condition-qualified and reproducible design-space framework for direct seawater electrolysis at an operational industrial range of 0.5 – 1.0 A cm⁻². Its first contribution is an evidence taxonomy that prevents raw neutral seawater, alkaline seawater, asymmetric feeds, ion-separated systems, and desalination-coupled

electrolysis from being compared as though they share one boundary. Its second contribution is a six-descriptor coupling model linking intrinsic kinetics, site exposure, chloride exclusion, passivation, transport, and microenvironment control to activity, selectivity, and retention. Its third contribution is a falsifiable gradient-architecture hypothesis.

The model-derived results show why balanced architectures deserve testing alongside single-function improvements. Among four prescribed archetypes, G1 gives 342.35 mV at 1.0 A cm⁻², 99.11% O₂ FE, 97.51% predicted 1,000 h retention, and ASS 91.42. Equation-level sensitivity indicates that intrinsic kinetics affects activity, chloride exclusion affects selectivity, and chloride exclusion with passivation affects stability. The results are theoretical inferences derived from four representative archetypes under literature-constrained model equations; large-scale design-space scanning remains a direction for future research. These trends are not experimental causal estimates.

The practical implication is that a high-rate seawater electrode should be engineered as a spatially integrated system: a conductive and adherent backbone, a robust electronic/passivation interlayer, a selectively reconstructing or stable OER phase, a charged microenvironment that regulates hydroxide and halides, and pores that remove gas and precipitates. No layer should be optimized without testing its effect on the others.

The limitations are substantial. The model is phenomenological, omits stack-scale transport and detailed chemistry, assumes constant degradation, and cannot certify a composition. All thresholds are hypotheses for experimental validation, not certified device specifications. Future work should begin with matched B1/E1/M1/G1-inspired electrodes in raw and alkaline seawater, three-electrode measurements, galvanostatic chronopotentiometry at 0.5 and 1.0 A cm⁻², calibrated O₂ and chlorine-product analysis, ion chromatography, ICP dissolution measurements, and optical bubble/deposit inspection. RRDE may help resolve transient chlorine chemistry. More demanding operando spectroscopy, tracer studies, microelectrode profiling, and cross-sectional ion mapping could subsequently probe the mechanism; extended continuous and intermittent durability and full-cell system comparison remain essential before practical claims.

REFERENCES

- [1] FEI H, et al. Direct Seawater Electrolysis: From Catalyst Design to Device Applications. *Advanced Materials*, 2024, 36(17): e202309211. DOI: 10.1002/adma.202309211.
- [2] LIU Y, et al. Long-term Durability of Seawater Electrolysis for Hydrogen: From Catalysts to Systems. *Angewandte Chemie International Edition*, 2024, 63(47): e202412087. DOI: 10.1002/anie.202412087.
- [3] ZHENG W, LEE L Y S, WONG K Y. Improving the performance stability of direct seawater electrolysis: from catalyst design to electrode engineering. *Nanoscale*, 2021, 13(36): 15177–15187. DOI: 10.1039/D1NR03294A.
- [4] KASANI A, et al. Catalysts for Direct Seawater Electrolysis: Current Status and Future Prospectives. *ChemElectroChem*, 2024, 11(9): e202300743. DOI: 10.1002/celec.202300743.
- [5] XIE H, et al. A membrane-based seawater electrolyser for hydrogen generation. *Nature*, 2022, 612: 673–678. DOI: 10.1038/s41586-022-05379-5.
- [6] LIN K, et al. Hydrogen production from seawater splitting enabled by on-line flow-electrode capacitive deionization. *Renewable and Sustainable Energy Reviews*, 2023, 183: 113525. DOI: 10.1016/j.rser.2023.113525.
- [7] JIANG S, et al. A 250-kilowatt system for co-production of hydrogen and fresh water from seawater. *Nature Energy*, 2026: advance online publication. DOI: 10.1038/s41560-026-02130-6.
- [8] HAUSMANN J N, et al. Is direct seawater splitting economically meaningful? *Energy & Environmental Science*, 2021, 14: 3679–3685. DOI: 10.1039/D0EE03659E.
- [9] LIU H, et al. High-Performance Alkaline Seawater Electrolysis with Anomalous Chloride Promoted Oxygen Evolution Reaction. *Angewandte Chemie International Edition*, 2023, 62(46): e202311674. DOI: 10.1002/anie.202311674.
- [10] BAHUGUNA G, PATOLSKY F. Routes to Avoiding Chlorine Evolution in Seawater Electrolysis: Recent Perspective and Future Directions. *ACS Materials Letters*, 2024, 6(8): 3202–3217. DOI: 10.1021/acsmaterialslett.4c00409.
- [11] JIN H, et al. Emerging materials and technologies for electrocatalytic seawater splitting. *Science Advances*, 2023, 9(42): eadi7755. DOI: 10.1126/sciadv.adi7755.
- [12] HORNER O, WILKINSON D P, GYENGE E L. Selectivity Study of Direct Seawater Electrolyzer Anode Catalysts Using the Rotating Ring-Disc Electrode Method. *Journal of The Electrochemical Society*, 2024, 171(9): 094502. DOI: 10.1149/1945-7111/ad7407.
- [13] DRESP S, NGO THANH T, KLINGENHOF M, BRÜCKNER S, HAUKE P, STRASSER P. Efficient direct seawater electrolyzers using selective alkaline NiFe-LDH as OER catalyst in asymmetric electrolyte feeds. *Energy & Environmental Science*, 2020, 13(6): 1725–1729. DOI: 10.1039/D0EE01125H.
- [14] JADHAV A R, et al. Stable complete seawater electrolysis by using interfacial chloride ion blocking layer on catalyst surface. *Journal of Materials Chemistry A*, 2020, 8(46): 24501–24514. DOI: 10.1039/D0TA08543J.
- [15] HUANG W, et al. Selective Anion-Gating Interlayer Enables Chloride-Resistant and Long-Life Alkaline Seawater Electrolysis. *Interdisciplinary Materials*, 2026, 5(1): 180–191. DOI: 10.1002/idm2.70031.
- [16] HE X, et al. Hexafluorophosphate additive enables durable seawater oxidation at ampere-level current density. *Nature Communications*, 2025, 16: 4998. DOI: 10.1038/s41467-025-60413-0.
- [17] TANG H, et al. Harnessing chloride to drive catalyst reconstruction for durable and efficient seawater electrolysis. *Nature Communications*, 2026, 17: 9098. DOI: 10.1038/s41467-026-76145-8.
- [18] GUO J, et al. Constructing an OH⁻-enriched microenvironment on the electrode surface for natural seawater electrolysis. *Nano Research*, 2024, 17(11): 9483–9489. DOI: 10.1007/s12274-024-6873-1.
- [19] GUO J, et al. Direct seawater electrolysis by adjusting the local reaction environment of a catalyst. *Nature Energy*, 2023, 8: 264–272. DOI: 10.1038/s41560-023-01195-x.
- [20] HE D, et al. Durable seawater electrolysis enabled by chloride rejection on hydroxide trapping anode. *Journal of Energy Chemistry*, 2025, 107: 407–415. DOI: 10.1016/j.jechem.2025.03.063.
- [21] CAI Z, et al. In Situ Microenvironment Engineering Enables Synergistic Suppression of Protons and Chloride for Durable Seawater Oxidation. *ACS Nano*, 2026, 20(12): 10210–10222. DOI: 10.1021/acsnano.6c01477.
- [22] TANVEER UL HAQ, et al. Microenvironment-Engineered Multilayered Electrode Design for Sustainable Seawater Oxidation. *Small*, 2025, 21: 2501376. DOI: 10.1002/smll.202501376.
- [23] ZHOU L, et al. A restricted dynamic surface self-reconstruction toward high-performance of direct seawater oxidation. *Nature Communications*, 2024, 15: 2481. DOI: 10.1038/s41467-024-46708-8.
- [24] YIN Z H, et al. Anionic Passivation Enables Reconstruction-Free Seawater Electrolysis. *Journal of the American Chemical Society*, 2026, 148(30): 32676–32690. DOI: 10.1021/jacs.6c10541.
- [25] CHANG J, et al. Dual-Doping and Synergism toward High-Performance Seawater Electrolysis. *Advanced Materials*, 2021, 33(33): 2101425. DOI: 10.1002/adma.202101425.
- [26] KANG X, et al. A corrosion-resistant RuMoNi catalyst for efficient and long-lasting seawater oxidation and anion exchange membrane electrolyzer. *Nature Communications*, 2023, 14: 3607. DOI: 10.1038/s41467-023-39386-5.
- [27] YIN S, et al. Suppressing oxygen-vacancy-mediated chlorine corrosion for high-current stable seawater electrolysis. *Chemical Science*, 2026, 17(1): 214–224. DOI: 10.1039/D5SC07816D.

- [28] DU J, et al. Anion Exchange Membrane Seawater Electrolysis at 1.0 A cm⁻² With an Anode Catalyst Stable for 9000 h. *Advanced Science*, 2025, 12(22): 2416661. DOI: 10.1002/adv.202416661.
- [29] ZHANG S, et al. Concerning the stability of seawater electrolysis: a corrosion mechanism study of halide on Ni-based anode. *Nature Communications*, 2023, 14: 4822. DOI: 10.1038/s41467-023-40563-9.
- [30] KOU T, et al. Periodic Porous 3D Electrodes Mitigate Gas Bubble Traffic during Alkaline Water Electrolysis at High Current Densities. *Advanced Energy Materials*, 2020, 10(46): 2002955. DOI: 10.1002/aenm.202002955.
- [31] LI L, et al. High-Rate Alkaline Water Electrolysis at Industrially Relevant Conditions Enabled by Superaerophobic Electrode Assembly. *Advanced Science*, 2023, 10(4): 2206180. DOI: 10.1002/adv.202206180.
- [32] LIANG J, et al. Efficient bubble/precipitate traffic enables stable seawater reduction electrocatalysis at industrial-level current densities. *Nature Communications*, 2024, 15: 2950. DOI: 10.1038/s41467-024-47121-x.
- [33] WANG C, et al. Heterogeneous bimetallic sulfides based seawater electrolysis towards stable industrial-level large current density. *Applied Catalysis B: Environmental*, 2021, 291: 120071. DOI: 10.1016/j.apcatb.2021.120071.
- [34] LIU T, et al. In-situ direct seawater electrolysis using floating platform in ocean with uncontrollable wave motion. *Nature Communications*, 2024, 15: 5305. DOI: 10.1038/s41467-024-49639-6.
- [35] KHAN M A, et al. Seawater electrolysis for hydrogen production: a solution looking for a problem? *Energy & Environmental Science*, 2021, 14: 4831–4839. DOI: 10.1039/D1EE00870F.
- [36] FAN R, et al. Ultrastable electrocatalytic seawater splitting at ampere-level current density. *Nature Sustainability*, 2024, 7: 158–167. DOI: 10.1038/s41893-023-01263-w.
- [37] LIU D, et al. Efficient and Ultrastable Seawater Electrolysis at Industrial Current Density with Strong Metal-Support Interaction and Dual Cl⁻-Repelling Layers. *Advanced Materials*, 2024, 36(49): 2408982. DOI: 10.1002/adma.202408982.
- [38] SHA Q, et al. 10,000-h-stable intermittent alkaline seawater electrolysis. *Nature*, 2025, 639: 360–367. DOI: 10.1038/s41586-025-08610-1.

Attribution Non-Commercial License 4.0 (CC BY-NC 4.0).

© The Author(s) 2026

ACKNOWLEDGEMENTS

The authors thank the researchers whose published findings informed this synthesis and the colleagues who offered constructive comments on the manuscript.

FUNDING

None.

AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Amirul Hakim bin Ramli: Conceptualization, literature review, model formulation, and writing — original draft. Danial Haikal bin Roslan: Literature synthesis, four-archetype calculations, visualization, and writing — review and editing. Chin Chee Keong: Supervision, methodological guidance, writing—review and editing, and correspondence. All authors reviewed and approved the final manuscript.

COMPETING INTERESTS

The author declares no competing interests.

Publisher's note WEDO remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is published online with Open Access by Green Design Engineering and distributed under the terms of the Creative Commons