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Alkaline Seawater Electrolysis at Industrial Level: Recent Progress and Perspective

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$\begin{array}{r} \text{\#} \quad \text{\#} \quad \text{\#} \\ \text{\#} \quad \text{\#} \quad \text{\#} \\ \text{DOI: 10.13208/j.electrochem.2214006}} \qquad \text{\#} \quad \text{http://electrochem.xml.edu.cn} \\ \text{Alkaline Seawater Electrolysis at Industrial Level:} \\ \text{\textbf{Recent Progress and Perspective}} \\ \text{Tao Zhang} \text{ in, Yi-Pu Liu} \text{\#}, Qi-Tong Ye} \text{, Hong-Jin Fan} \text{Fan} \text{'} \end{array}$ **Example 2020**
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DOI: 10.13208/j.electrochem.2214006
 **Recent Progress and Perspective

Recent Progress and Perspective

ao Zhang¹⁴, Yi-Pu Liu²⁴, Qi-Tong Ye², Hong-Jin** $\frac{d}{dt}$ $\frac{d}{dt}$

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Tao Zhang^{1#}, Yi-Pu Liu^{2#}, Qi of 18)

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 Alkaline Seawater Electrolysis at Industrial Level:
 Recent Progress and Perspective
 Singapore 637371, Singapore; 2. State Key Laboratory of Marine Resource Utilization in South China Sea, **EVALUATE SCHOOL OF ALSO ANTIFICATES SCIENCES SCIE**

Abstract: Industrial hydrogen generation through water splitting, powered by renewable and marined through water splitting and λ as solar of λ and λ and λ $\begin{tabular}{c|c|c} u & u& \mathcal{H}\\ & & L~Elementem, 2022, 281(0), 2214006 (1 of 18)\\ \hline \hline \end{tabular} \vline \rule{0mm}{0.5cm} \vspace{0.2cm} \v$ **Example the CONDUM CONSUMER CONSUMER CONSUMERATION**

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Tao Zhang^{ja}, Yi-Pu Liu³⁶, Qi-Tong Ye³, Hong-Jin Fan¹

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Tao Zhang^{is}, Yi-Pu Liu², Qi-Tong Ye², Hong-Jin Fan^{*}

(*I. School of Physical and Mathematical Sciences, Nawyam Technologica* Friedrich Coca overcet Extert of Justice in Transformation Cocasing The Cocasing Theorem (1. School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore; 2. **Kecent Progress and Perspective**

Tao Zhang^u, Yi-Pu Liu²⁸, Qi-Tong Ye², Hong-Jin Fan¹

(1. School of Physical and Mahematical Sciences, Nanyang Technological University, 21 Nanyang Link,

Singapore 6.23271, Singa School of Materials Science and Engineering, Hainan University, Haikoto 570228 P. R. China)

Stract: Industrial hydrogen generation through water splitting, powered by renewable energy such as solar, wind and marine,

es **Abstract:** Industrial hydrogen generation through water splitting, powered by renewable energy such as solar, wind and marine,
paves a potential way for energy and environment sustainability. However, state-of-the-art el **Abstract:** Industrial hydrogen generation through water splitting, powered by renewable energy such as solar, wind and
paves a potential way for energy and environment sustainability. However, state-of-the-art electrolysi on through water splitting, powered by enewable energy such as solar, wind and marine,
nment sustainability. However, state-of-the-art electrolysis using high purity water as hy-
bring about criss of freshwater resource. **Abstract:** Industrial hydrogen generation through water splitting, powered by enewable energy such as solar, wind and marine,
paves a potential way for energy and environment sustainability. However, state-of-the ent ele pares a potential way for energy and environment sustainability. However, state-of-the-art electrolysis using high purity water as hy-
drogen source at an industrial bevel would bring about crisis of freshwart resource. Se drogen source at an industrial level would hring about crisis of freshwater resource. Seaware splitting provides a practical path to
solve potable water shorting, everting general mechanisms, design eriteria for electrodes solve pointle water abortange, but still faces great challenges for large-scale industrial decreasion examplement of excelents in examplement of the particular ters phenoment of the sterior derivative propartic trep situat gyang recrinological University, 21 Natryang Link,

f Marine Resource Utilization in South China Sea,

nan University, Haikou 570228 P. R. China)

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 nan University, Haikou 570228 P. R. China)

powered by renewable energy such as solar, wind and marine,

vever, state-of-the-art electrolysis using high purity water the consumption of H₂ gas produced by seawater splitting consumption Direct electrolysis with a solar, wind and marine, wever, state-of-the-art electrolysis using high purity water as hy-
water resource. Seawater splitt powered by renewable energy such as solar, wind and marine,
vever, state-of-the-art electrolysis using high purity water as hy-
water resource. Seawater splitting provides a practical path to
scale industrial operation. H

Large-scale electrochemental variation in the consumption of H₅ gas produced by sourced (Hy) by renewable electricity, characterized the consumption of H₅ gas produced by sourcedry by high energy cleasiv (142 MJ-kg⁻¹ hydrogen (H₃) by renewable electricity, characterized
the consumption of H₅ gas produced by
ship, nergy density (142 MJ-kg⁻¹) and zero emiss-
spiriling can produce fresh potable water annot
sisted, both has been reg **I Introduction** link electrochemical scawater electrolysis to these

Large-scale electrochemical water splitting into environmental friendly technologies^[7,8] Additionally,

sydrogen (H₂) by renewable electricity, ch **roduction**

Imk electrochemical seawater electrolysis to these-scale electrochemical water splitting into

miximum (H₂) by renewable electricity, characterized

the consumption of H₂ gas produced by seawater

energy ments in seawater splitting, covering general mechanisms, design criteria for electrodes, and industrial electrolyzer for direct seawa-
ter splitting-Multi-objective opimization methods to address the key challenges of se ter splitting Multi-ohjerive opimization mefiods to addess the key challenge of active sies, reaction selectivity, conventor is users, of the party and stealing the total stearchies to design direct devices for long-time tance, and mass transfer ability will be diseased. The recent development in sawware electrolyers and equaint efficient strategies
to design direct devices for long-time operation are also highlighted. Finally, we provide in a casya mental estables are nonegament are naw in agreement in a casya and considered to the section of the sectio **Examples are are served example to the ocean of the ocean of the served to the ocean of the served electrolysis is the phydrogen (H₂) by renewable electrologies and environmental firedly technologies^{7.91}. Additionall EXECUTE:** Many working solar energy), and the state of the state

1 Introduction link electrochemical seawater electrolysis to these powered by renewable energy such as solar, wind and marine,
vever, state-of-the-art electrolysis using high purity water as hy-
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wever, state-of-the-art electrolysis using high purity water as hy-
water resource. Seawater splitting provides a practical path to
scale industrial opera mustain the source Seawater splitting provides a practical path to scale industrial operation. Here we summarize recent develop-
teria for electrodes, and industrial electrolyzer for direct seawa-
challenges of active sit scale industrial operation. Here we summarize recent develop-
teria for electrodes, and industrial electrolyzer for direct seawa-
challenges of active sites, reaction selectivity, corrosion resis-
pment in seawater electr teria for electrodes, and industrial electrolyzer for direct seawa-

challenges of active sites, reaction selectivity, corrosion resis-

pment in seawater electrolyzer and acquaint efficient strategies

Finally, we provid allenges of active sites, reaction selectivity, corrosion resistent in seawater electrolyzer and acquaint efficient strategies
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ageneration; industrial electroly ment in seawater electrolyzer and acquaint efficient strategies
Finally, we provide our own perspective to future opportunities
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mixed areas environmental friendly technologies^[7,8] Finally, we provide our own perspective to future opportunities
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link electrochemical seawater electrolysis to these
environmental friendly technologies^[7,8]. Additionally,
the consumption of H₂ gas produced by seawater
splitting can produce gen generation, intustant electrolysis to these
environmental friendly technologies^[78]. Additionally,
the consumption of H₂ gas produced by seawater
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 $# \&L \# (J. Electron.) 2022, 28(10), 2214006 (2 of 18)$

are still grand challenges to meet the above standard. Thus, the OER-only potential window

These challenges include:

1) *High cost of raw materials*. Pt-based nanoparti-

cles then $\#k\#(J. \nElet\nmean.)\n2022, 28(10), 2214006 (2 of 18)\n\nwith the inducti-
\nse challenges include:\n\n1) High cost of raw materials. Pt-based nanoparti-
\nas rate-of-the-art hydrogen evolution reaction\n\n2) Slugish mass transfer process. The industry
\nBRS electrocatalysts, while IrRu-based oxides are\n2) level current densities would accelerate the consump-
\nsidered as commercial electrocatalysts for oxygen\n\n3) the system of the result of the model. The same system is used to use a new
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\nthick of the model. The same system is used to use a new state-of-the-art high-costalysts for oxygen
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These challenges include:
1) *High cost of rawe materials*. Pt-based nanoparti-
1) *High cost of r* $\pm \ell \neq (L \quad Electrochem.) 2022, 28(10), 2214006 (2 of 18)$
are still grand challenges to meet the above standard. Thus, the OFR-only potential window in the industri-
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are still grand challenges to meet the above standard. Thus, the OER-only potential window in the industri-

These challenges include:

1) *High cost of row materials* $4!R^{22}(L)E(createchen, 2022, 28(10), 2214006 (2 of 18)$ are still grand challenges to meet the above standard. Thus, the OER-only potential window in the industri-
These challenges include:

al seawater splitting should be widened as cles are state-of-the-art hydrogen evolution reaction

(IIER) electrocatalysts, while In/Ru-based oxides are

coveragn tion different densities would accelerate the core

considered as commercial electrocatalysts for oxyg

librium potential of OER (E_{OER}^0) is more negative Although many excellent reviews are available on considered as commercial electrocatalysts for oxygen

constant and accumulation of gaseous

colution rozeion (OER). The scarity and high cost products on the clerctod surface¹⁰¹. In this case, str-

of these noble-metal evolution reaction (OER). The scarcity and high cost

of these noble-metal based materials restrict their

large-seal industrial application¹⁶¹³¹,

are discussed industrial application¹⁶¹³,

2D *Insufficient performan* 0 – E_{CER}^{0} , where a 100% OER splitting systems at i of these noble-metal based materials restrict their
argeies are needed to manipulate the adsorption of
arge-scale industrial application $e^{(2)}$.
Based in detail application $e^{(2)}$.
Based in the activity is correlated to large-scale industrial application¹⁶⁴³¹. Scattolyte on the eatalyst surface and desorption of

2) Insufficient performance of electrocatalysts. The gas bubbles by microstructure engineering.

intrinsic etatyite activity 2) Insufficient performance of electrocatalysts. The gas bubbles by microstructure engineering.

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harmic catalytic ferr intrinsic catalytic activity is correlated to the energy

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the the above standard. Thus, the OER-only potential window in the industri-
These challenges include:
These challenges include:
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Thus, the OER-only potential window in the industri-
al seawater splitting should be widened as much as
possible.
4) Sluggish mass transfer process. The industry
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Thus, the OER-only potential window in the industri-

al seawater splitting should be widened as much as

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4) Sluggish mass transfer process. The industry

level current densities wo possible. 电化学(*J. Electrochem.*) 2022, 28(10), 2214006 (2 of 18)

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These challenges include:
 Solution the state-of-the-art hydrogen evolution reaction
 EVALUATION IS at the state-of-the-art hydrogen evol 2) Insufficient performance of electrocatalysts. The **Example 19**
 Example 19 the $\#t\#(L$ Electronchem.) 2022, 28(10), 2214006 (2 of 18)

are still grand challenges to meet the above standard. Thus, the OER-only potential window in the industri-

These challenges include:

1) High cost of raw mat $8(10)$, 2214006 (2 of 18)
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4) *Sluggish mass transfer process*. The industry
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Thus, the OER-only potential window in the industri-

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Thus, the OER-only potential window in the industri-

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4) *Sluggish mass transfer process*. The industry level current densities would accelera 2, 28(10), 2214006 (2 of 18)

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Thus, the OER-only potential window in the industrial

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4) *Sluggish mass transfer process*. The industry level current densities would accelerate the consumption of reactant ions

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Thus, the OER-only potential window in the industri-

These challenges include:
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These challenges include:

1) High cost of rate materials. Pt-based nanoparti-

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These challenges include:

The standard active political sequel spitting should be widened as much as

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Since a 1) *High cost of raw materials*. Pt-based nanoparti-
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clear are state-of-the-art hydrogen covoliton reactio 1 evolution reaction

4) *Sluggish mass transfer process*. The industry

Ru-based oxides are

level current densities would accelerate the consump-

catalysts for oxygen

ion of reactant ions and accumulation of gaseous
 (HER) electrocatalysts, while Ir/Ru-based oxides are level current densities would accelerate the consump-
considered as commercial electrocatalyss for oxygen into of reactant ions and accumulation of gaseous
coolution re is exactive and high cost products on the electrode surface^[21]. In this case, strematerials restrict their ategies are needed to manipulate the adsorption of electrocatalysts. The electrolyte on the catalyst surface an 2, 28(10), 2214006 (2 of 18)

Thus, the OER-only potential window in the industrial

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4) Sluggish mass transfer process. The industry

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Thus, the OER-only potential window in the industrial

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4) *Sluggish mass transfer process*. The industry
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regies are need level current densities would accelerate the consump-
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ategies are needed to manipulate the adsorption of
electro tion of reactant ions and accumulation of gaseous
products on the electrode surface^[21]. In this case, str-
ategies are needed to manipulate the adsorption of
electrolyte on the catalyst surface and desorption of
gas bu products on the electrode surface^[21]. In this case, strategies are needed to manipulate the adsorption of electrolyte on the catalyst surface and desorption of gas bubbles by microstructure engineering.
5) *Corrosion a* ategies are needed to manipulate the adsorption of
electrolyte on the catalyst surface and desorption of
gas bubbles by microstructure engineering.
5) Corrosion and catalyst deterioration. Besides the
unavoidable corrosion electrolyte on the catalyst surface and desorption of
gas bubbles by microstructure engineering.
5) Corrosion and catalyst deterioration. Besides the
unavoidable corrosion of chloride (CI-) ions on both
electrodes, the met gas bubbles by microstructure engineering.
5) Corrosion and catalyst deterioration. Besides the
unavoidable corrosion of chloride (CI-) ions on both
electrodes, the metal ions in seawater including mag-
nesium (Mg^{2;}), c 5) Corrosion and catalyst deterioration. Besides the unavoidable corrosion of chloride (CI-) ions on both electrodes, the metal ions in seawater including magnesium (Mg²⁺), calcium (Ca²⁺), et al., and even bacteria, m

⁰). catalysts development for wate

 $\#E\#(J. Electron, 2022, 28(10), 2214006 (3 of 18)$
ting. We first introduce the fundamental of seawater netically sluggish than the two-electron involved
electrolysis, well-accepted descriptors, and anticorro-
correction ability fo [†] † *H k*²[#] (*L Electrochem.*) 2022, 28(10), 2214006 (3 of 18)
 electrolysis, well-accepted descriptors, and anticorro-
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electrolysis, well-accepted descriptors, and anti

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ing. We first introduce the fundamental of seawater and cally sluggish than the two-electron involved

electrolysis, well-accepted descriptors, and anticorro-

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electrolysis, well-accepted descriptors, and anticorro-
cCER, thus the CER in the seawater might complete
cison ability for se ting. We first introduce the fundamental of seawater
electrolysis, well-accepted descriptors, and anticorro-

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CFR, thus the CFR in electrolysis, well-accepted descriptors, and anticorro-

EER, thus the CER in the sign of the disign criteria of seawater originality for seawater description, eathofor HER.

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CER, thus the CER in the seawater might complete

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night the design criteria of seawater e sion ability for seawater oxidation, cathode HER. With OFR at the anode and lower the overall efficien-
Then, we lightlight the design critical of seawater electrolysis and in-dependent
celectrolysis equipment, and the pr Then, we highlight the design criteria of seaware corrosions contained electrolysis. An in-depth understand-
electrodysis equipment, and the problems existing in ign of the above four main reaction mechanisms
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Then, we highlight the design criteria of seawater $\frac{f(R) + f(R) \leq 2.28(10), 2214006 (3 of 18)}{2.28(10), 2214006 (3 of 18)}$

ting. We first introduce the indentental of seawater are ideally sluggish than the two-electron involved

electrolysis, well-accepted descriptors, and antic current electrolytic cells and general solutions. Finally, $#E\ddot{\varphi}(L\text{Electrochem.}) 2022, 28(10), 2214006 (3 of 18)$
ting. We first introduce the fundamental of seawater metically sluggish than the two-electron involved
electrolysis, well-accepted descriptors, and anticorro-
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 EXAMPLE 12 $\#R\#(L \nvert \text{Electro} \leq 28(10), 2214006 (3 of 18)$

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electrolysis, well-accepted descriptors, and anticorro-

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 Example 199 $8(10)$, 2214006 (3 of 18)

netically sluggish than the two-electron involved

CER, thus the CER in the seawater might compete

with OER at the anode and lower the overall efficien-

cy of seawater electrolysis. An in-dep $8(10)$, 2214006 (3 of 18)

netically sluggish than the two-electron involved

CER, thus the CER in the seawater might compete

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with OER at the anode and lower the overall efficien-

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CER, thus the CER in the seawater might compete

with OER at the anode and lower the overall efficien-

cy of seawater electrolysis. An in-dep $8(10)$, 2214006 (3 of 18)

netically sluggish than the two-electron involved

CER, thus the CER in the seawater might compete

with OER at the anode and lower the overall efficien-

evo of seawater electrolysis. An in-de $x(10)$, 2214006 (3 of 18)

antically sluggish than the two-electron involved

CER, thus the CER in the seawater might compete

with OER at the anode and lower the overall efficien-

evo of seawater electrolysis. An in-de 0), 2214006 (3 of 18)

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R, thus the CER in the seawater might compete

h OER at the anode and lower the overall efficien-

of seawater electrolysis. An in-depth understand-
 $8(10)$, 2214006 (3 of 18)

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with OER at the anode and lower the overall efficien-

cy of seawater electrolysis. An in-de $8(10)$, 2214006 (3 of 18)

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CER, thus the CER in the seawater might compete

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CER, thus the CER in the seawater might compete

with OER at the anode and lower the overall efficien-

cy of seawater electrolysis. An in-dept 8(10), 2214006 (3 of 18)

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main reaction mechanisms

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ration of efficient seawater

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with OER at the anode and lower the overall efficien-
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ing of the above four main reaction mechanisms
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lysis. An in-depth understand-

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electrode corrosion) is crucial

eparation of efficient seawater

Il as electrolyzers.
 Seawa 电化学(*J. Electrochem.*) 2022, 28(10), 2214006 (3 of 18)

undamental of seawater netically sluggish than the two-electron involved

scriptors, and anticorro- CER, thus the CER in the seawater might compete

dation, cathodi

with OER at the anode and lower the overall efficien-

cy of seawater electrolysis. An in-depth understand-

ing of the above four main reaction mechanisms

(HER, OER, CER and electrode corrosion) is crucial

for the desi cy of seawater electrolysis. An in-depth understand-
ing of the above four main reaction mechanisms
(HER, OER, CER and electrode corrosion) is crucial
for the design and preparation of efficient seawater
electrocatalysts, in-depth understand-
reaction mechanisms
the corrosion) is crucial
in of efficient seawater
trolyzers.
er
ermal dynamics from
teps, the anodic OER
is water decomposition.
at an anode for either
media (eqns. (6)-(10))
(1

(2)

$$
2MO_{ads} \to 2M + O_2 \tag{3}
$$

$$
MOads + H2O \rightarrow MOOHads + H+ + e-
$$
 (4)

$$
MOOHads + OH- \rightarrow M + O2 + H2O + e-
$$
 (10)

the $(2\pi + 1)$ of θ of θ or $\$ **EXECTE CONFIRE THE CONFIRM (FOR A DETA)**
 ANOOH₁₈ + H₂O → M + O₂ + H³ + C (5) by the developed theoretical and experimental re-

Reaction in alkaline media:
 A direct combination of the Pouthain end in the C (4) $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and the correlation of the sequeration of the sequeration of the other refers to the sequeration of the other refers to the sequeration of the competi $\text{H}_2\text{H}_2\text{H}_3 = \text{H}_2\text{H}_3 = \text{H$

(3) and (8)), and the other refers to the generation of

The thermodynamic potential window for OFR

sequently decompose into O_E. (4) and (9)) which sub-

satel). However, under alkaline conditions, the cquilibrium

seq MOOH intermediates (eqns. (4) and (9)) which sub-
send CER is only 130 mV at pH = 0 (the equilibrium
compared with the electrolysis of pure water, sea-
hibrium potential of CER does not rely on the pH
vater splitting is m scquently decompose into O.

compared with the electrolysis of pure water, sea-

Compared with the electrolysis of pure water, sea-

ibitum potential of CER does not rely on the pH

water splitting is more challenging in Compared with the electrolysis of pure water, sea-

birium potential of CER doss not rely on the pH

or the diverge spling in smood callenging in consideration

or and the divergence rallenging in consideration

or for di water splitting is more challenging in consideration

of the diverse components, especially the high con-

certain of choices components, especially the high con-

certain of choices any based of the diverse competi-

of of the diverse components, especially the high concreases up to 480 mV (Figure 2b and 2c Case i). Thus,

centration of chloride amions, which would not only alkaline seawatte electrolysis is usually used as a

bring about centration of chloride anions, which would not only

bring about the unwanted CER but also cause severe

experimentance can general design criterion. As memioned above, OFR

berromsion to many metallic electrodes. The comp bring about the unwanted CER but also cause severe

corrections. The competi-

actions in emande is at four electron-proton transfer process

cion mechanism has been explored for many decades.

and shows more sluggish rea corrosion to many metallic electrodes. The competi-

id an anode is a four electron-proton transfer process

for mechanism has been explored for many decades. and shows more sluggish reaction kinetics than CER

In 1980, B tion mechanism has been explored for many decades, and shows more sluggish reaction kineties than CER

In 1980, Bennet pioncered the selective OER in sea-

water by a procous manganese-hased electrode, but

the range of t In 1980, Bennet pioneered the selective OER in sea-
which is a two electron-proton reaction. In this case,
where by a porous manganes-based electrode, but the range of the OER-only potential window shows a
only using acid water by a porous mangenese-based electrode, but
the range of the OFR-only potential window shows a
only using acide seaware as an electrolyte¹³¹. The distaic drop (e.g., \approx 200 mV for IrO_N, as illustrated
electroly only using acidic seawater as an electrolyte^[27]. The drastic drop (e.g., \approx 200 mV for IrO₂), as illustrated
electrolysis performed in unbuffred seawater dis-
in Figure 2c, Case i¹²⁹¹, However, the industrial app electrolysis performed in unbuffered seawater dis-
in Figure 2c, Case ii²⁴¹. Ilowever, the industrial appli-
played a priority of CRR at higher current densities. ention for seawater splitting should be that to DER-
The played a priority of CER at higher current densities, cation for seawater splitting should be that the OER-
The OER-only window was located only at lower only potential window should be widened as much as
current density o The OER-only window was located only at lower
only potential window should be widened as much as
uct easily or at very high one dat to severe CER possible for promoting the OER and suppressing the
ones t-ransfer limitions

 $\#E \# (J. Electrochem.) 2022, 28(10), 2214006 (4 of 18)$ MOOH_{ads} + H₂O → M + O₂ + H⁺ + e⁻ (5) by the developed theoretical and experimenta

Reaction in alkaline media:

M + OH⁻ → MOH_{ads} + e⁻ (6) the competition between $# \&L \# (J. \t{Electrochem.}) 2022, 28(10), 2214006 (4 of 18)$ + e⁻ (5) by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of (6) the competition between OER and CER (Figure 2b)^[18] (5) by the developed theoretical and experimental re- $\text{MOOH}_{\text{ads}} + \text{H}_2\text{O} \rightarrow \text{M} + \text{O}_2 + \text{H}^+ + \text{e}^-$ (5) by the developed theoretical and exp

Reaction in alkaline media:
 $\text{Meck} + \text{OH}^- \rightarrow \text{MOH}_{\text{ads}} + \text{e}^-$
 $\text{MOH}_{\text{ads}} + \text{OH}^- \rightarrow \text{MOH}_{\text{ads}} + \text{H}_2\text{O} + \text{e}^-$
 \text $\text{HOOH}_{\text{ads}} + \text{H}_2\text{O} \rightarrow \text{M} + \text{O}_2 + \text{H}^+ + \text{e}^-$ (5) by the developed theoretical and exper

Reaction in alkaline media:

M + OH⁻ → MOH_{ads} + e⁻ (6) by the developed theoretical and exper

sults, Dionigi et al (6) the competition between OER and CER (Figure 2b)^[18]. $H_2(E \ncong (J. Electrochem.) 2022, 28(10), 2214006 (4 of 18)
\n MOOH_{uds} + H₂O → M + O₂ + H⁺ + e⁻ (5) by the developed theoretical and experimental re-
\n Reaction in alkaline media:
\n M + OH⁻ → MOH_{ads} + e⁻ (6) the competition between OER and CER (Figure 2b)¹⁸
\n MOH_{ads} → OH →H₂ + e⁻ (7) A description of the construction of the Pourbaix dia
\n$ (7) A description of the construction of the Pourbaix dia- $\text{H}(E \ncong (J. Electrochem.) 2022, 28(10), 2214006 (4 of 18)$

MOOH_{nsh} + H₂O → M + O₂ + H⁺ + e⁻ (5) by the developed theoretical and experience in alkaline media:

Natro Di malkaline media:

M + OH → MOH_{nsh} + e⁻ (6) the (8) gram for chlorine species is available by the follow- $\begin{array}{lllllllllllll} & & & \text{#1}E\#^2(J. Electrochem.) & 2022, 28(10), 2214006 (4 of 18)\\ \hline \text{MOOH}_{\text{sub}} + H_2O \rightarrow M + O_2 + H^+ + e^- & & & & \text{(5)} & \text{by the developed theoretical and experiment}\\ \text{Reaction in alkaline media:} & & & \text{suffix, Dionigi et al. conducted an in-depth anal;\\ M + OH^- \rightarrow MOH_{\text{sub}} + e^- & & & & \text{(6)} & \text{the competition between OER and CER (Figure MOH}_{\text{sub}} + OH^- \rightarrow MO_{\text{sub}} + H_2O + e^- & & &$ (9) ing equations. $\text{H}(B \to B)$
 $\text{H}(B \to B$ $\text{HOOH}_{\text{lab}} + \text{H}_2\text{O} \longrightarrow \text{M} + \text{O}_7 + \text{H}^+ + \text{e}^-$ (5) by the developed theoretical and experimental re-

Reaction in alkaline media:

Reaction in alkaline media:
 $\text{M} + \text{OH}^- \rightarrow \text{MO}_{\text{lab}} + \text{e}^-$ (6) the competitio $\text{H}_2\text{H}_2\rightarrow \text{H}_2\rightarrow \text{H}_$ 2, 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the construction 2, 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental re-
sults, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the constructi 2, 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental re-
sults, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the constructi 2, 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the construction 2, 28(10), 2214006 (4 of 18)
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the competition between OER and CER (Figure 2b)^[18].

A description of the construct 2. 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the construction 18)

heoretical and experimental re-

onducted an in-depth analysis of

een OER and CER (Figure 2b)^[18].

construction of the Pourbaix dia-

ecies is available by the follow-

medium:
 $e^0 = 1.36 \text{ V} \text{ vs. SHE, pH} = 0 \text{ (11)}$ 2. 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b^[18].
A description of the construction 2. 28(10), 2214006 (4 of 18)

by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of

the competition between OER and CER (Figure 2b)¹⁸⁾.

A description of the constructi $2(10)$, 2214006 (4 of 18)
 t the developed theoretical and experimental re-

Its, Dionigi et al. conducted an in-depth analysis of

e competition between OER and CER (Figure 2b)¹⁸⁾.

description of the construction o 8(10), 2214006 (4 of 18)
the developed theoretical and experimental re-
ts, Dionigi et al. conducted an in-depth analysis of
competition between OER and CER (Figure 2b)^[18].
description of the construction of the Pourba 2. 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)¹⁰⁸.
A description of the construction $\frac{\text{H} \& \frac{2022}{1000}}{\text{H} \& \frac{2022}{10000}} = \frac{222}{10000} \times \frac{2214006}{10000} \times \frac{4000}{10000} \times \frac{4000}{10000} \times \frac{4000}{10000} \times \frac{4000}{10000}} \times \frac{2000}{10000} \times \frac{4000}{10000} \times \frac{4000}{10000}} \times \frac{4000}{1000} \times \frac{400}{100$

Reaction in an acidic medium:

EVALUATION THE CONTRACT (S) by the developed the of the electronical and experimental re-

Reaction in alkaline media:

Reaction in alkaline media:

Native Decomposition between OER and CER (Figure 2h^{pps}).

MOH_{Aa} + MOOH_{ia} + H₃O \rightarrow M + O₂ + H⁴ + e² (5) by the developed theoretical and experimental re-

Reaction in alkaline media:

M + OH² \rightarrow MOH_{ia} + e² (6) the competition between OER and CER (Figure 2b)¹⁹¹.

MOH MOOH₄₆ + H₂O → M + O₂ + H² + c² (5) by the developed theoretical and experimental re-

Reaction in alkaline media:

M + OH⁺ → MO₄₆ + H₂O + e² (6) the competition between OFR and C-freq Trigure 2 by¹⁹¹. Reaction in alkaline media:

Subs, Dionigi et al. conducted an in-depth analysis of

Mr OH: \rightarrow MOH_{ab} + σ (6) the competition between OER and CER (Figure 2b^{y®},

MOH_{ab} + OH: \rightarrow MO_{ab} + H₂O + c⁺ (7) A descr M + OII⁻ → MOII_{-a} + e²
 $\text{MOH}_{\text{high}} + \text{OH}^* \rightarrow \text{Me}_\text{high} + \text{H}_2\text{O} + \text{c}$ (5) the competition between OER and CER (Figure 2h)^{[04}]
 $\text{MOH}_{\text{high}} + \text{OH}^* \rightarrow \text{Mo}_\text{high} + \text{H}_2\text{O} + \text{c}$ (8) gram for choinne species MOH_{Las} + OH¹ --> MO_{As} + H₂O + e⁻

2MO_{As} -- 2M+ - _O₂ + C₁² + O₁² + C₁² (8) gymm for cholors epecies is available by the follow-

2MO_{BH} + OH⁻ -> MOOH_{ka} + c-H⁻ -> MOOH_{ka} + c¹ (9) ing e 2MO_{th} \rightarrow 2M + O_t + e⁻ MOTH_C + e⁻ (8) gram for chlorine species is available by the follow-
MO_{CH₀ + OH⁺ \rightarrow MOOH₁₆ + e⁻ (10) ing equations.
Here M represents the active sites, It should be noted 2Cl} MO_{an}: OH⁻ \rightarrow MOOH_{an}: le²

MOOH_{an}: HOH \rightarrow M+ O₂ + H₂O + c²

Here M represents the active sites. It should be noted and 2CI \rightarrow C₁ + 2c² \rightarrow Eⁿ = 1.36 V vs. SHE, pH = 0 (11)

that two different a MOOH_{4a} + OH \rightarrow M + O₂ + H₂O + c' (10) Reaction in an acidic medium:

Here M represents the active sines. It should be noted $2C1 \rightarrow C1$; $12\pi c$ $E'' = 1.36$ V vs. SHE, pH = 0 (11)

that two different approaches to fo Here M represents the active sites. It should be noted

Here M represents to fifter an probable in two different approachs to from Mo in-

termediates would occur (Figure 2a)²⁴. One route is via Cit +2OH -4 ClO + H₂O that two different approaches to form O, from MO in-Reaction in an alkaline medium:

termediates would occur (Figure 2a)²⁴. One route is via $C1^+ + 2OH^- \to C10^- + H_00 + 2C$

a direct combination of MO-MO to rclease O₂ (can termediates would occur (Figure 2a)^{ies}. One route is via $Ct^2 \rightarrow C10^- + H_2O + 2c$

d a direct combination of MO-MO to release O_L (eqns. $R^{\text{P}} = 0.89$ V vs. SHF₁, pH = 14 (3) and (8)), and the other refers to the gene a direct combination of MO-MO to release O₂ (eqns. $E^2 = 0.89$ V vs. SHE; pH = 14 (12)

(3) and (8)), and the other refers to the generation of The thermodynamic potential window for DER

(MOOH intermediates (eqns. (4) ethed alkaline conditional states and the developed states).

Substate dia all the developed and experimental results, Dionigi et al. conducted an in-depth analysis of the competition between OER and CER (Figure 2b)^[18] 2. 28(10), 2214006 (4 of 18)
by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the construction range, and the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of the competition between OER and CER (Figure 2b)^[18].
A description of the construction of the Pourbaix diag by the developed theoretical and experimental results, Dionigi et al. conducted an in-depth analysis of the competition between OER and CER (Figure 2b)^[18]. A description of the construction of the Pourbaix diagram for sults, Dionigi et al. conducted an in-depth analysis of
the competition between OER and CER (Figure 2b)^[18].
A description of the construction of the Pourbaix dia-
gram for chlorine species is available by the follow-
i the competition between OER and CER (Figure 2b)^[18].
A description of the construction of the Pourbaix dia-
gram for chlorine species is available by the follow-
ing equations.
Reaction in an acidic medium:
 $2CI \rightarrow Cl_2 + 2e$ A description of the construction of the Pourbaix dia-
gram for chlorine species is available by the follow-
ing equations.
Reaction in an acidic medium:
 $2CI \rightarrow CI_2 + 2e^ E^0 = 1.36$ V vs. SHE, $pH = 0$ (11)
Reaction in an a gram for chlorine species is available by the follow-
ing equations.
Reaction in an acidic medium:
 $2CI \rightarrow CI_2 + 2c^ E^0 = 1.36$ V vs. SHE, $pH = 0$ (11)
Reaction in an alkaline medium:
 $CI+2OH \rightarrow CIO \rightarrow H_2O + 2c^-$
 $E^0 = 0.89$ V vs. ing equations.

Reaction in an acidic medium:
 $2CI \rightarrow CI_2 + 2e^ E^0 = 1.36$ V vs. SHE, pH = 0 (11)

Reaction in an alkaline medium:
 $CI^{-} + 2OH^{-} \rightarrow ClO^{-} + H_2O + 2e^-$
 $E^0 = 0.89$ V vs. SHE, pH = 14 (12)

The thermodynamic potent Reaction in an acidic medium:
 $2CI \rightarrow CI_2 + 2e^ E^0 = 1.36$ V vs. SHE, pH = 0 (11)

Reaction in an alkaline medium:
 $CI^{-} + 2OH^{-} \rightarrow ClO^{-} + H_2O + 2e^-$
 $E^0 = 0.89$ V vs. SHE, pH = 14 (12)

The thermodynamic potential window for O 2Cl⁻ → Cl₂ + 2e⁻ $E^0 = 1.36$ V vs. SHE, pH = 0 (11)

Reaction in an alkaline medium:

Cl⁻ + 2OH⁻ → ClO⁻ + H₂O +2e⁻
 $E^0 = 0.89$ V vs. SHE, pH = 14 (12)

The thermodynamic potential window for OER

and CER Reaction in an alkaline medium:
 $Cl^- + 2OH^- \rightarrow ClO^- + H_2O + 2e^-$
 $E^0 = 0.89$ V vs. SHE, $pH = 14$ (12)

The thermodynamic potential window for OER

and CER is only 130 mV at $pH = 0$ (the equilibrium

state). However, under alkal Cl⁻ + 2OH⁻ → ClO⁻ + H₂O + 2e⁻
 E^0 = 0.89 V vs. SHE, pH = 14 (12)

The thermodynamic potential window for OER

and CER is only 130 mV at pH = 0 (the equilibrium

state). However, under alkaline conditions, the $E^0 = 0.89$ V vs. SHE, pH = 14 (12)
The thermodynamic potential window for OER
and CER is only 130 mV at pH = 0 (the equilibrium
state). However, under alkaline conditions, the equi-
librium potential of CER does not rely The thermodynamic potential window for OER
and CER is only 130 mV at $pH = 0$ (the equilibrium
state). However, under alkaline conditions, the equi-
librium potential of CER does not rely on the pH
range, and the thermodyn and CER is only 130 mV at $pH = 0$ (the equilibrium
state). However, under alkaline conditions, the equi-
librium potential of CER does not rely on the pH
range, and the thermodynamic potential window in-
creases up to 4 state). However, under alkaline conditions, the equi-
librium potential of CER does not rely on the pH
range, and the thermodynamic potential window in-
creases up to 480 mV (Figure 2b and 2c Case i). Thus,
alkaline seawa rium potential of CER does not rely on the pH
ge, and the thermodynamic potential window in-
asses up to 480 mV (Figure 2b and 2c Case i). Thus,
alaline seawater electrolysis is usually used as a
aneral design criterion. range, and the thermodynamic potential window in-
creases up to 480 mV (Figure 2b and 2c Case i). Thus,
alkaline seawater electrolysis is usually used as a
general design criterion. As mentioned above, OER
at an anode is creases up to 480 mV (Figure 2b and 2c Case i). Thus,
alkaline seawater electrolysis is usually used as a
general design criterion. As mentioned above, OER
at an anode is a four electron-proton transfer process
and shows alkaline seawater electrolysis is usually used as a
general design criterion. As mentioned above, OER
at an anode is a four electron-proton transfer process
and shows more sluggish reaction kinetics than CER
which is a tw general design criterion. As mentioned above, OER
at an anode is a four electron-proton transfer process
and shows more sluggish reaction kinetics than CER
which is a two electron-proton reaction. In this case,
the range at an anode is a four electron-proton transfer process
and shows more sluggish reaction kinetics than CER
which is a two electron-proton reaction. In this case,
the range of the OER-only potential window shows a
drastic d

and shows more sluggish reaction kinetics than CER
which is a two electron-proton reaction. In this case,
the range of the OER-only potential window shows a
drastic drop (e.g., ≈ 200 mV for IrO,), as illustrated
in Fig which is a two electron-proton reaction. In this case,
the range of the OER-only potential window shows a
drastic drop (e.g., ≈ 200 mV for IrO₂), as illustrated
in Figure 2c, Case ii^[25]. However, the industrial ap the range of the OER-only potential window shows a
drastic drop (e.g., ≈ 200 mV for IrO₂), as illustrated
in Figure 2c, Case ii^[25]. However, the industrial appli-
cation for seawater splitting should be that the O drastic drop (e.g., ≈ 200 mV for IrO₂), as illustrated
in Figure 2c, Case ii²⁵¹. However, the industrial appli-
cation for seawater splitting should be that the OER-
only potential window should be widened as much in Figure 2c, Case ii²⁵¹. However, the industrial application for seawater splitting should be that the OER-
only potential window should be widened as much as
possible for promoting the OER and suppressing the
CER simu cation for seawater splitting should be that the OER-
only potential window should be widened as much as
possible for promoting the OER and suppressing the
CER simultaneously (Figure 2c Case iii).
2.2 Cathodic Hydrogen Ev only potential window should be widened as much as
possible for promoting the OER and suppressing the
CER simultaneously (Figure 2c Case iii).
2.2 **Cathodic Hydrogen Evolution Reaction**
Despite the previous investigations .

EVALUATION 1989
 EVALUATION 1992, 28(10), 2214006 (5 of 18)
 COMPATE:

MCL_i + OH⁻ → M(CL_i + OH⁻ → M(OH)₄ + Cl⁻

MT-H₁₄₆ + e⁻ → M-H₁₄₆ + OH⁻ (13) M refers to the metal active sites at

MY-WORSN st).

performance of the electrode materials^[33]. The formace of the decetrode materials^[33]. The formace of mining the limited access

inhibited through optimizing the operating parameters Δ as alternatives, transition
 tion of hydroxide precipitates during HER can be

inhing the limited access to seawar

inhibited through optimizing the operating parameters

to bothin superior coverall catalytic performance of

electrode, including addi

 $-$ (15))^[18].

(18)

 $\# \# \# (J. \ \t{Electrochem.}) 2022, 28(10), 2214006 (5 of 18)$ Volmer step:

M + H₂O + e⁻ → M-H_{ats} +OH⁻ (13) M refers to the metal acti

Heyvrosky step:

M-H_{ats} + H₂O + e⁻ → H₂ + M + OH⁻ (14) (14) crial active sites M + H2O + e- [→] M-Hads +OH- (13) M refers to the metal active sites at the electrode. $\frac{\text{#L#}(J. Electrochem.) 2022, 28(10), 2214006 (5 of 18)}{\text{Volmer step:}}$ Volmer step:

M + H₂O + e⁻ → M-H_{ats} + OH⁻ (13) M refers to the metal active

Heyvrosky step:

M + H_{ats} + H₂O + e⁻ → H₂ + M + OH⁻ (14) crystal lattic $H_2(E\#(J. Electron, 2022, 28(10), 2214006 (5 of 18))$ Wolmer step:

M + H₂O + e⁻ → M-H_{als} + OH⁻ (13) M refers to the metal active sites at the electro

Heyvrosky step:

M refers to the metal active sites at the electro

Hage (14) crystal lattice, leading to lattice distortion, structure $H^2H^2(L \tElectrochem.) 2022, 28(10), 2214006 (5 of 18)$

Volmer step:
 $M + H_2O + e^- \rightarrow M - H_{ads} + OH^-$
 $H = M + H_2O + e^- \rightarrow H_2 + M + OH^-$
 $H = M + H_{ads} + H_2O + e^- \rightarrow H_2 + M + OH^-$
 $H = M + H_{ads} + H_2O + H_2 + M + OH^-$
 $H = M + H_{ads} + M - H_{ads} + M$ $\frac{d}{dx} \mathcal{H} = \frac{d}{dx} \math$ **EVACULA FRANCE (***LETE CONGONG ELECCION CONGONG CONGONG ELECCION CONGONG CONGONG CONGONG CONGONG CONGONG CONGONG CON* **EACTIVE EXAMULT 1000** (5 of 18)

Wolmer step:

Wolmer step:

M+H₂O + c⁻ → M-H_{2a} + OH⁻ (13)

M+H₂O + c⁻ → M₊H_{2a} + OH⁻ (13)

M refers to the metal active sites at the electrode.

Heyvrosky step:

M-H_{2a} precipitates on electrode due to the presence of **EVALUATION 1999**
 EVALUATION EVALUATE (2) Electrochem, 2022, 28(10), 2214006 (5 of 18)

Volmer step:

M+H₃O + c⁻ → M-H₃₆+OH⁻ (13) M refers to the metal active sites at the electrode.

Heyrosky step:

Hywrosky step:

M+H₃₆ + C+ + H₂+ + $8(10)$, 2214006 (5 of 18)

MCl_x⁻ + OH⁻ → M(OH)_x + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice dis $8(10), 2214006$ (5 of 18)

MCl_x + OH⁻ → M(OH)_x + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice distorti 8(10), 2214006 (5 of 18)

MCl_x + OH⁻ \rightarrow M(OH)_x + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice distor 18)

(OH)_x + Cl⁻ (18)

hetal active sites at the electrode.

ions may even incorporate into the

ding to lattice distortion, structure

we sites deactivation^[34]. Thus, how to

neture stability is another great 8(10), 2214006 (5 of 18)

MCl_x⁻ + OH⁻ → M(OH)_x + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice distor $8(10), 2214006 (5 of 18)$
 $MCl_x^- + OH^- \rightarrow M(OH)_x + Cl^-$ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice distortion, structure

in $8(10), 2214006$ (5 of 18)

MCl_x⁻ + OH⁻ → M(OH)_x + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice disto challenge. $8(10)$, 2214006 (5 of 18)

MCl_s + OH⁻ → M(OH)_s + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

erystal lattice, leading to lattice distort $8(10)$, 2214006 (5 of 18)

MCl_s + OH⁻ → M(OH)_s + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

crystal lattice, leading to lattice distort 0), 2214006 (5 of 18)

CL_k⁻+ OH⁻ → M(OH)_k+ Cl⁻ (18)

refers to the metal active sites at the electrode.

procver, the Cl⁻ ions may even incorporate into the

stal lattice, leading to lattice distortion, struc $8(10), 2214006$ (5 of 18)

MCl_x⁺ OH⁻ \rightarrow M(OH)_x⁺ Cl⁻

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

erystal lattice, leading to lattice distorti $\text{H}(L\#(J. \text{Electrochem.}) 2022, 28(10), 2214006 (5 of 18)$ MCl_x⁻ + OH⁻ → M(OH)_x + Cl⁻ (18)

(13) M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

cDH- (14) cr

EACAL Electrochem.) 2022, 28(10), 2214006 (5 of 18)

There step:

The major scenario and the magnitude steps to the metal active sites at the electroche.

However, the Cl⁺ coms may even incorporate into the

H_{as} + H **FROM THE THE VALUE (1** External 2022, 28(10), 2214006 (5 of 18)

Wolmer step:
 $M+H_2O + c \rightarrow M+H_{ab} + OH$
 $M+H_3O + c \rightarrow H_2 + M + OH$

(13) M refers to the metal active sites at the electrode.

Heyrosky step:
 $M+H_{ab} + H_4O + c \rightarrow H_2 + M + OH$ H(E\phi (E+1) Electrochem.) 2022, 28(10), 2214006 (5 of 18)

M+H₅O + c⁻→ M-H₃₀+OH⁻ (13)

M+H₅O + c⁻→ M-H₃₀+OH⁻ (13)

M+H_{5O} + c⁻→ M-H₃₀+OH⁻ (14)

M+H_{6O} + c⁻→ H₂+ M + OH⁻ (14)

M+H_{6O} + c Volume step:

Volume step:

When the electrode materials of the electrode materials of the electrode.

Heyrosky step:

M+Fig. + e' → H₃+OH⁻ (13) M refers to the metal active sites at the electrode.

Heyrosky step:

M-Volmer step:

Volme Tape: $MCl_x^+ + OH^-$ (18)

M+1H₂0+ e⁻⁻ $-$ M+1-a₁+ e-1H² (13)

Mereover, the C1 ions may even incorporate into the

Heryrosky step:

M+R₃₆+ H₂0+ e⁻ - H₂+ M + OH² (14) eryrstal lattice, le $M + H_2O + e \rightarrow M + H_{ab} + OH$ (13) M refers to the metal active sites at the electrode.

Heywrosky step:

Heywrosky step:

M-H_{oth} + H, + O+ M+ OH

(14) crystal lattice, leading to lattice distortion, structure

Tafel step:

M-H Heyworsky step:

Heyworsky step:

M-H_{wa}+ H₁+ M+ OH

Tafel step:

M presents the active sites. However, there are two

challeng M-H_{at} + H₂O + c \rightarrow H₂+ M + OH² (14) crystal lattice, leading to lattice distortion, structure

Instability and additivers detectrode instability and additivers detectrode M-H_{at} + M-H_{at} \rightarrow H₂+ 2M (15) mai Tafel step:
 M-H_{am} \rightarrow H₂+2M

M-H_{am}^{\rightarrow} H_{am}^{\rightarrow} H_{am}^{\rightarrow} Ham shows that the structure stability is another great

M-presens the active sites. However, there are two challenge.

main challenges in seawate $M=H_{adv} + M+H_{adv} \rightarrow H_z + 2M$ (15) maintain the structure stability is another great

M presents the ecity sites. However, there are two conditings.

main challenges in seaware HFR: (1) deposition of **3.1 Activity** M presents the active sites. However, there are two challenge.

mean challenges in seawarter HER: (1) deposition of **3 Design Criteria for Electrode**

mean challenges in seawater. HER: (1) deposition of **3 Design Criteria** main challenges in seawater HER: (1) deposition of **3 Design Criteria for Electrode**
precipitates on electrode the to the presence of **3.1 Activity of Catalysts for OER and HER**
precipitates on electrode due to the presen precipitates on electrode due to the presence of

aladinic errit metallic ions, basetica, microbes, and

almoin small particles in secondary (2) electrode corrosion by

small particles in secondary (2) electrode corrosion alkaline certh metallic ions, baeteria, microbes, and

metalle are instant particles in seaware correstion by

smalle particles in section contration concentration concentration

smaller concentration concentration while small particles in seawater; (2) electrode corrosion by

unions (fauto₂) and iridium dioxide (ftrO₂) have been

unions (mainly from CT).

The major problem is related to the precipitates

from various dissolved metal considered as state-of-the-art electrocatalysts for

The major problem is related to the precipitates

from various dissolved metal cations such as Mg^2 ,

sever oxidation, but their high cost and scarity

from various d The major problem is related to the precipitates

water oxidation, but their high cost and scarcity

from various dissolved metal cations such as $M_B^{\circ +}$, severely impede their large-scale application¹³⁹. In

for α from various dissolved metal cations such as Mg^{2s} , severely impede their large-scale application¹⁸⁹. In
erformance of the electrode materials⁹⁰¹. The forma-
enerformance of the electrode materials⁹⁰¹. The forma-Ca²; Ph²; Cu²; et al., which suppresses the catalytic

edition, the theoretical overpotential of OER (0.59

performance of the electrode materials¹⁹. The forma-

tion of hydroxide precipitates during The forma-

t ibited through optimizing the operating parameters

obtain supreme of the proved more suitable for seawater splitting

obtain supreme or overall catalytic performance of

etcrological control contently, γ -NiOOH is the he operating parameters

as alternatives, transition metal compounds have

not been proved more suitable for seawater splitting^{03, xs-w}

or buffer solution that

for enerthy, γ -NiOOH is the widely accepted real

fore to obtain superior overall catalytic performance of

been proved more suitable for seawater splitting^{p2358}n

electrocol_{os} including additives or buffer solution that Currently, γ -NiOOH is the widely accepted real
 electrode, including additives or buffer solution that

correctly, γ -NiOOH is the widely accepted real

induce pre-precipitation before clectrolysis or dating active phase for Ni-based OER catalysts after surface

stab induce pre-precipitation before electrolysis and
stative phase for Ni-based OER catalysts after surface
seawater. Moreover, Kirk et al. showed that high cultaines demonstrate that weak CI' ions adsom-
seawater. Moreover, SECUTE THE SECUTE SECUTE ANOTE CONDINET THE ADSORPTION SURVENTION (FC-4 OPEN CHET AROSTETION)

SURFACUTE THE ANOTE (THE AROSTET (FOR SURFACUTE THE ANOTE CONDUSTANT THE PRECISION OF INTERFERENCE THEOREM CONDUST CONDUST CO ver, Kirk et al. showed that high

culations demonstrate that the weak Cl⁻ ions a

lectrolyte and large applied current

tion on γ -NiOOH (Fe-dopped γ -NiOOH) ext

able for inhibiting the precipitate

inders the pot duid flow rate of electrolyte and large applied current

tion on γ -NiOOH (Fe-dopped γ -NiOO

density are favorable for inhibiting the precipitate

formation at high solution concentration while the lowever, Fe-dopped (16) spices optimized the generation of *OOH step and density are favorable for inhibiting the precipitate

formation at high solution concentration while the

total precipitate

toreactive is proportional to the ionic catalytic activity for OER, sign

toencentration in seaw formation at high solution concentration while the

toral precipitate is proportional to the ionic

concentration in sexuater¹⁹³. Additionally, membrane and

concentration in sexuater $\frac{1}{2}$ actual OER-only potential (17) $mA \cdot cm^{-2}$ with nearly 100% O₂ Faradaic efficiency in total precipitate is proportional to the ionic

catalytic activity for OER, sign

concentration in seawater¹⁵²¹. Additionally, membrane

permsechective membrane have also been approved observation enchange membrane

of $8(10)$, 2214006 (5 of 18)

MCl_s⁺ OH⁻ \rightarrow M(OH)_s+ Cl⁻

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ions may even incorporate into the

drives interaction, structure

instability and 8(10), 2214006 (5 of 18)

MCl_s + OH⁻ → M(OH)_s + Cl⁻

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

erystal lattice, leading to lattice distortion, st $8(10)$, 2214006 (5 of 18)

MCl_x⁺ OH⁻ \rightarrow M(OH)_x + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

erystal lattice, leading to lattice d $8(10), 2214006$ (5 of 18)

MCl₄ + OH⁻ → M(OH)_{*n*} + Cl⁻ (18)

M refers to the metal active sites at the electrode.

Moreover, the Cl⁻ ions may even incorporate into the

erystal lattice, leading to lattice distor EVALUATE: $+OH^- \rightarrow M(OH)_* + Cl^-$ (18)

M refers to the metal active sites at the electrode.

Moreover, the CI ions may even incorporate into the

crystal lattice, leading to lattice distortion, structure

instability and active MCl_a⁻⁺ OH⁻ → M(OH)_a+ Cl⁻ (18)
M refers to the metal active sites at the electrode.
Moreover, the Cl⁻ ions may even incorporate into the
crystal lattice, leading to lattice distortion, structure
instability and M refers to the metal active sites at the electrode.
Moreover, the Cl⁻ ions may even incorporate into the crystal lattice, leading to lattice distortion, structure instability and active sites deactivation^[34]. Thus, Moreover, the Cl⁻ ions may even incorporate into the
erystal lattice, leading to lattice distortion, structure
instability and active sites deactivation^[34]. Thus, how to
maintain the structure stability is another gr . crystal lattice, leading to lattice distortion, structure
instability and active sites deactivation^[34]. Thus, how to
maintain the structure stability is another great
challenge.
3. Design Criteria for Electrode
3.1 instability and active sites deactivation^[34]. Thus, how to
maintain the structure stability is another great
challenge.
3. Design Criteria for Electrode
3.1 Activity of Catalysts for OER and HER
The noble-metal bas maintain the structure stability is another great
challenge.
3. Design Criteria for Electrode
3.1 Activity of Catalysts for OER and HER
The noble-metal based oxides such as ruthenium
dioxide (RuO₂) and iridium dioxi challenge.
 3 Design Criteria for Electrode
 3.1 Activity of Catalysts for OER and HER

The noble-metal based oxides such as ruthenium

dioxide (RuO₂) and iridium dioxide (IrO₂) have been

considered as state-of-t Figure 2. and HER

as ruthenium
 h_2) have been

catalysts for

and scarcity

cation^[35]. In

f OER (0.59

FIO₂, deter-

lectrolysis^[25].

bounds have

plitting^[23, 36-39].

ccepted real

after surface
 V (DFT **3 Design Criteria for Electrode**
 3.1 Activity of Catalysts for OER and HER

The noble-metal based oxides such as ruthenium

dioxide (RuO₂) and iridium dioxide (IrO₂) have been

considered as state-of-the-art elect 3.1 Activity of Catalysts for OER and HER
The noble-metal based oxides such as ruthenium
dioxide (RuO₂) and iridium dioxide (IrO₂) have been
considered as state-of-the-art electrocatalysts for
water oxidation, but the The noble-metal based oxides such as ruthenium
dioxide (RuO₂) and iridium dioxide (IrO₂) have been
considered as state-of-the-art electrocatalysts for
water oxidation, but their high cost and scarcity
severely impede dioxide (RuO₂) and iridium dioxide (IrO₂) have been
considered as state-of-the-art electrocatalysts for
water oxidation, but their high cost and scarcity
severely impede their large-scale application^{[181}. In
additio considered as state-of-the-art electrocatalysts for
water oxidation, but their high cost and scarcity
severely impede their large-scale application^{[181}. In
addition, the theoretical overpotential of OER (0.59
eV) surpas water oxidation, but their high cost and scarcity
severely impede their large-scale application^{[151}. In
addition, the theoretical overpotential of OER (0.59
eV) surpasses that of CER (0.28 eV) for IrO₂, deter-
mining severely impede their large-scale application^{[181}. In
addition, the theoretical overpotential of OER (0.59
eV) surpasses that of CER (0.28 eV) for IrO₂, deter-
mining the limited access to seawater electrolysis^{[29}]. addition, the theoretical overpotential of OER (0.59
eV) surpasses that of CER (0.28 eV) for IrO₂, deter-
mining the limited access to seawater electrolysis¹²⁵.
As alternatives, transition metal compounds have
been pr eV) surpasses that of CER (0.28 eV) for IrO₂, determining the limited access to seawater electrolysis¹²⁵.
As alternatives, transition metal compounds have been proved more suitable for seawater splitting^{[23,36,39}]. mining the limited access to seawater electrolysis^[25].
As alternatives, transition metal compounds have
been proved more suitable for seawater splitting^{[23,36,39}].
Currently, γ -NiOOH is the widely accepted real
ac As alternatives, transition metal compounds have
been proved more suitable for seawater splitting^{23,36,39}.
Currently, γ -NiOOH is the widely accepted real
active phase for Ni-based OER catalysts after surface
reconstr been proved more suitable for seawater splitting^{[23,36,39}].
Currently, γ -NiOOH is the widely accepted real
active phase for Ni-based OER catalysts after surface
reconstruction. Density functional theory (DFT) cal-
cu Currently, γ -NiOOH is the widely accepted real
active phase for Ni-based OER catalysts after surface
reconstruction. Density functional theory (DFT) cal-
culations demonstrate that the weak Cl⁻ ions adsorp-
tion on active phase for Ni-based OER catalysts after surface
reconstruction. Density functional theory (DFT) cal-
culations demonstrate that the weak Cl⁻ ions adsorp-
tion on γ -NiOOH (Fe-dopped γ -NiOOH) extremely
hinders reconstruction. Density functional theory (DFT) calculations demonstrate that the weak Cl⁻ ions adsorption on γ -NiOOH (Fe-dopped γ -NiOOH) extremely hinders the potential-determining step of OER. However, Fe-dopped culations demonstrate that the weak Cl⁻ ions adsorption on γ -NiOOH (Fe-dopped γ -NiOOH) extremely hinders the potential-determining step of OER. However, Fe-dopped γ -NiOOH shows better intrinsic catalytic activi tion on γ -NiOOH (Fe-dopped γ -NiOOH) extremely
hinders the potential-determining step of OER.
However, Fe-dopped γ -NiOOH shows better intrinsic
catalytic activity for OER, significantly enlarging the
actual OER-on hinders the potential-determining step of OER.
However, Fe-dopped γ -NiOOH shows better intrinsic
catalytic activity for OER, significantly enlarging the
actual OER-only potential window. Inspired by
doping strategies, However, Fe-dopped γ -NiOOH shows better intrinsic
catalytic activity for OER, significantly enlarging the
actual OER-only potential window. Inspired by
doping strategies, Li et al. developed a multilayered
oxygen-evolu catalytic activity for OER, significantly enlarging the
actual OER-only potential window. Inspired by
doping strategies, Li et al. developed a multilayered
oxygen-evolution electrode with metaborate-modified
 γ -(Ni,Fe)O

 $\frac{\text{H}(\frac{\text{L}\omega}{\epsilon})}{\text{H}(\frac{\text{L}\omega}{\epsilon})}$ (*L Electrochem.*) 2022, 28(10), 2214006 (6 of 18)
 Pt-based electrocatalysts are by far considered as

can well maintain the catalytic activity and stability

the most effecti reserve, thus restricting their industrial application [41] **EVALUATION 1989**
 EVALUATION 1999
 EVALUATION \pm 162 $\frac{2}{5}$ (*L Electrochem.*) 2022, 28(10), 2214006 (6 of 18)

Pt-based electrocatalysts are by far considered as can well maintain the eatalytic activity and stability

the most effective electrode materials for H(k^2 ²(*J. Electrochem.*) 2022, 28(10), 2214006 (6 of 18)

Pt-based electrocatalysts are by far considered as can well maintain the catalytic activity and stability

the most effective electrode materials for HER but $\text{ft}(\mathbb{R}^{\infty})$
 Example 19
 Exam ± 0.42 . Electrodem, 2022, 28(10), 2214006 (6 of 18)

Pt-based electrocatalysts are by far considered as

can well maintain the catalytic activity and stability

the most effective electrode materials for HER but

at a **EVALUATION 11**
 EVALUATION EVALUATION EVALUATI the $\mathcal{R}^{\pm}(L \kappa_{\text{f}}/L \kappa_{\text{$ $4k^2$, k^2 , $k^$ **EVERTUAL EXAMONT THE CONSUMATE (SET ALL ACT AND A SUPPOSE THE CONSUMPTED THE ABOVE ON THE CONDUCT THE ART AND THE CONDUCT TH 11.** $\frac{d}{dt}E^{\infty}(J. \text{E}I_{c} \cdot \$ $\frac{4\pi}{4}E^{2\pi}(L \text{ Rlectrochem}) \times 222, 28(10), 2214006 (6 of 18)$

Pt-based electrocatalysts are by far considered as

can well maintain the catalytic activity and stability

the most effective electrode materials for HER but at a Pt-based electroceatalysts are not well as shown in the catalytic etcivity and stability
the most effective electrode materials for HER but at a high constant turent density of 500 mA-cm⁻² in
still face many drawbacks i Pt-hased electrocatalysts are by far considered as

an well maintain the catalytic activity and stability

the most effective electrofe matrixis for HER but at high constant current density of 500 mA em² in

still face the most effective electrode materials for HFR but

at a high constant current density of 500 mA·cm⁻³ in

still fine many drawbucks including high price and low

better affinity and the diffinite natural seasons

Every, still face many drawhacks including high price and low

both alkaline natural seawater and alkaline sailine

respect, thus restricting their industrial application³⁶¹. electrolytiss. Qiao's group up forward a nickel

Fi reserve, thus restricting their industrial application.^{an} dectrolytes. Qiao's group put forward a nickel
Even the electrolytis occurs in seawater, the HER surface intride electrocatally with unsaturated Ni-N
mechanism i Even the electrolysis occurs in seawater, the HER surface nitride electrocatalyst with unsaturated Ni-N
nechanism is same as that in purity water. The bonds for alkaline seawater spliting (Figure 3b)⁶⁹.
well-established mechanism is same as that in purity water. The bonds for alkaline seawater splitting (Figure)-Iestablished Volcano polt can still act as a Promisingly, a two-electrode electrolyzer sy

sycretimize illustration of Sabatier well-established Volcano plot can still act as a Promisingly, a two-electrode electrolyzer system that
quantitative illustration of Sabative pinciple for coupled with hydrazine oxidation at the anode
screening electrode ma quantitative illustration of Sabatier principle for coupled with hydrazine oxidation at the anode
sercening electrode materials (Figure 2c)^{26, 26}, 7ms, requires a cell volage of conly 0.7 V to achieve a high
an active s serecening electrode materials (Figure 2c)^{(9,4,41}). Thus, requires a cell voltage of only 0.7 V to achieve a high
an active site should have neither to strong por too courred density of 1000 nA -em⁻². Caution should b an active site should have neither too strong nor too
werrent density of 1000 mA-cm⁻³. Caution should be
veck bind with H² ($\Delta\epsilon_{\text{tot}} = 0$). Alloying Pt_R group ackets are if these transition metal compounds will be weak bind with $H^* (\Delta G_{\mu r} = 0)$. Alloying Pt group taken if these transition metal compounds will be specieve with transition metals (Fe, Co, Ni, Cu, and Ti) electrode
metally coxidized on the surface under an enote onl stability[47]. ot only can drastically enhance the catalytic activity
 EV Ph-hasd allowed electrocatalyts via downshifting significant in OER process than in HER.
 EP d-band center but also enhance the corrosion Unlike the tradition of Pt-based alloyed electrocatalysts via downshifting significant in OER process than in HER.

the Pt d-band center but also enhance the corrosion

thick the transition metal nation transition and the signed-atom catalyst the Pt d-band center but also enhance the corrosion

Unlike the traditional nanostructured electrocataly-

resistance (^{6,3,1}, As shown in the Voleano plot, com-

say, the single-dato modulized for Cashyeli maximum

pare resistance^{(19,48}). As shown in the Volcano plot, com-

are, the single-atom catalysts (SACs) exhibit maximum

plenter affinity with H*. Hence, the development on a atom utilization and active site exposure, which are

b parcd with other transition metals, metallic Ni has a atom utilization and active site exposure, which are are different affinity with $1!$. Hence, the development on fravoriable for catalytic reaction. Transition metal
N better affinity with H^* . Hence, the development on favorable for catalytic reaction. Transition metal
Ni-based alloys is a preferred alternative way to SACs, such as Co^R¹⁰N¹⁰N¹M₀⁰², lave been
Ni-MoN nanostr

Ni-based alloys is a preferred alternative way to $SACs$, such as Co^{39} , $N1^{30}$, $M0^{402}$, and W^{50} , have been
reduce the use of Pt group materials. For instance, a widely investigated for HER in alkaline freshwate reduce the use of Pt group materials. For instance, a

widely investigated for HFR in alkaline freshwater,

NiMoN annorstructure catalyst can recach a high bur rarely used in seawater. For example, Zung et al.

surrent de NiMoN amostructure estalyst can reach a high

bout rarely used in seawater. For example, Zang et al.

current density of 1000 mA 'emi-a an overpendental pioneered highly disspeed Ni atoms coordinated

of 170 mV in simulat current density of 1000 mA - cm⁻³ at an overpotential pioneered highly dispersed Ni atoms coordinated
of 170 mV in simulated seawate²⁰⁰. In addition to the with triple nitrogen (Ni-N) as an effective HER electrode.
Fo of 170 mV in simulated seawater⁹⁹. In addition to the with triple nitrogen (Ni-N₃) as an effective HFR electrocion and intrinsic activity enhancement, the correct reduction and infinite activity changes to active in t cost reduction and intrinsic activity enhancement, the

etrode in seawater, which exhibited lower overpoten-

feasibility of introducing a third transition metal into itial than Ni-N: in seawater electrolyte (Figure 3c)[[] feasibility of introducing a third transition metal into

facing the harmy domain, such as PtA_BCo¹⁸⁰, PRINCo⁶⁶⁶, and

It is still a question fiber transition metal SACs are

PRINCo, endows the electrode superior str a binary domain, such as $PtAgCo¹⁸¹ PRRO¹⁸⁹$, and

It is still a question if these transition metal SACs are

tendico, endows the electrode superior structural

tendicological restabling they can be stable under alk PINiCo, endows the electrode superior structural

scapitive for industry-level current densities and if

stability^{ten},

Recent experimental and theoretical results illustrate

Recent experimental and theoretical results

 $\frac{d}{dt}\mathcal{H}$ Electrochem.) 2022, 28(10), 2214006 (6 of 18)

Pt-based electrocatalysts are by far considered as can well maintain the catalytic activity and stability

in most effective electrode materials for HER but at the most effective dectrocatalysts are by far considered as
 Pt-based electrocatalysts are by far considered as
 Consider constant to the most effective electrode materials for HER but

at a high constant current dens 2, 28(10), 2214006 (6 of 18)

can well maintain the catalytic activity and stability

at a high constant current density of 500 mA \cdot cm⁻² in

both alkaline natural seawater and alkaline saline

electrolytes. Qiao's gro 2, 28(10), 2214006 (6 of 18)

can well maintain the catalytic activity and stability

at a high constant current density of 500 mA \cdot cm⁻² in

both alkaline natural seawater and alkaline saline

electrolytes. Qiao's g in 2, 28(10), 2214006 (6 of 18)

can well maintain the catalytic activity and stability

at a high constant current density of 500 mA \cdot cm⁻² in

both alkaline natural seawater and alkaline saline

electrolytes. Qiao's g 2, 28(10), 2214006 (6 of 18)

can well maintain the catalytic activity and stability

at a high constant current density of 500 mA·cm⁻² in

both alkaline natural seawater and alkaline saline

electrolytes. Qiao's group 2, 28(10), 2214006 (6 of 18)

can well maintain the catalytic activity and stability

at a high constant current density of 500 mA \cdot cm⁻² in

both alkaline natural seawater and alkaline saline

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at a high constant current density of 500 mA·cm⁻² in
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at a high constant current density of 500 mA·cm⁻² in

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at a high constant current density of 500 mA·cm⁻² in

both alkaline natural seawater and alkaline saline

electrolytes. Qiao's group ctivity and stability
of 500 mA · cm⁻² in
and alkaline saline
forward a nickel
th unsaturated Ni-N
ing (Figure 3b)^[49].
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ion at the anode
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: Caution should be
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e 2, 28(10), 2214006 (6 of 18)

can well maintain the catalytic activity and stability

at a high constant current density of 500 mA·cm⁻² in

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at a high constant current density of 500 mA \cdot cm⁻² in

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n well maintain the catalytic activity and stability

a high constant current density of 500 mA \cdot cm⁻² in

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at a high constant current density of 500 mA \cdot cm⁻² in
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surface at a high constant current density of 500 mA \cdot cm⁻² in
both alkaline natural seawater and alkaline saline
electrolytes. Qiao's group put forward a nickel
surface nitride electrocatalyst with unsaturated Ni-N
bonds fo both alkaline natural seawater and alkaline saline
electrolytes. Qiao's group put forward a nickel
surface nitride electrocatalyst with unsaturated Ni-N
bonds for alkaline seawater splitting (Figure 3b)^[49].
Promisingly, electrolytes. Qiao's group put forward a nickel
surface nitride electrocatalyst with unsaturated Ni-N
bonds for alkaline seawater splitting (Figure 3b)⁽⁴⁹⁾.
Promisingly, a two-electrode electrolyzer system that
coupled 电化学(*J. Electrochem.*) 2022, 28(10), 2214006 (6 of 18)
by far considered as can well maintain the catalytic activity and stability
aterials for HER but at a high constant current density of 500 mA·cm⁻² in
mg high price

purity water. The bonds for alkaline seawater splitting (Figure 3b)^[49], an still act as a Promisingly, a two-electrode electrolyzer system that tier principle for coupled with hydrazine oxidation at the anode ure $2e^{0$ surface nitride electrocatalyst with unsaturated Ni-N
bonds for alkaline seawater splitting (Figure 3b)¹⁴⁹.
Promisingly, a two-electrode electrolyzer system that
coupled with hydrazine oxidation at the anode
requires a bonds for alkaline seawater splitting (Figure 3b)¹⁴⁹⁾.
Promisingly, a two-electrode electrolyzer system that
coupled with hydrazine oxidation at the anode
requires a cell voltage of only 0.7 V to achieve a high
current Promisingly, a two-electrode electrolyzer system that
coupled with hydrazine oxidation at the anode
requires a cell voltage of only 0.7 V to achieve a high
current density of 1000 mA \cdot cm⁻². Caution should be
taken i coupled with hydrazine oxidation at the anode
requires a cell voltage of only 0.7 V to achieve a high
current density of 1000 mA · cm⁻². Caution should be
taken if these transition metal compounds will be
electrochemica requires a cell voltage of only 0.7 V to achieve a high
current density of 1000 mA \cdot cm⁻². Caution should be
taken if these transition metal compounds will be
electrochemically oxidized on the surface under an
alkali current density of 1000 mA \cdot cm⁻². Caution should be
taken if these transition metal compounds will be
electrochemically oxidized on the surface under an
alkaline condition, which has been shown to be more
significan taken if these transition metal compounds will be
electrochemically oxidized on the surface under an
alkaline condition, which has been shown to be more
significant in OER process than in HER.
Unlike the traditional nanos electrochemically oxidized on the surface under an alkaline condition, which has been shown to be more significant in OER process than in HER.

Unlike the traditional nanostructured electrocataly-

sts, the single-atom ca alkaline condition, which has been shown to be more
significant in OER process than in HER.
Unlike the traditional nanostructured electrocataly-
sts, the single-atom catalysts (SACs) exhibit maximum
atom utilization and a mificant in OER process than in HER.
Unlike the traditional nanostructured electrocataly-
the single-atom catalysts (SACs) exhibit maximum
m utilization and active site exposure, which are
orable for catalytic reaction. T Unlike the traditional nanostructured electrocataly-
sts, the single-atom catalysts (SACs) exhibit maximum
atom utilization and active site exposure, which are
favorable for catalytic reaction. Transition metal
SACs, such sts, the single-atom catalysts (SACs) exhibit maximum
atom utilization and active site exposure, which are
favorable for catalytic reaction. Transition metal
SACs, such as $Co^{[50]}$, Ni^[51], Mo^[52], and W^[53], have b atom utilization and active site exposure, which are
favorable for catalytic reaction. Transition metal
SACs, such as $Co^{[50]}$, Ni^[51], Mo^[52], and W^[58], have been
widely investigated for HER in alkaline freshwater favorable for catalytic reaction. Transition metal

SACs, such as $Co^{[50]}$, Ni^[51], Mo^[52], and W^[53], have been

widely investigated for HER in alkaline freshwater,

but rarely used in seawater. For example, Zang e SACs, such as Co^[50], Ni^[51], Mo^[52], and W^[53], have been
widely investigated for HER in alkaline freshwater,
but rarely used in seawater. For example, Zang et al.
pioneered highly dispersed Ni atoms coordinated
 widely investigated for HER in alkaline freshwater,
but rarely used in seawater. For example, Zang et al.
pioneered highly dispersed Ni atoms coordinated
with triple nitrogen (Ni-N₃) as an effective HER ele-
ctrode in s

bility. oncered highly dispersed Ni atoms coordinated
th triple nitrogen (Ni-N₃) as an effective HER ele-
ode in seawater, which exhibited lower overpoten-
1 than Ni-N₄ in seawater electrolyte (Figure 3c)^{154]}.
is still a qu with triple nitrogen (Ni-N₃) as an effective HER electrode in seawater, which exhibited lower overpotential than Ni-N₄ in seawater electrolyte (Figure 3c)^[54]. It is still a question if these transition metal SACs a ctrode in seawater, which exhibited lower overpotential than Ni-N₄ in seawater electrolyte (Figure 3c)^[54]. It is still a question if these transition metal SACs are competitive for industry-level current densities an tial than Ni-N₄ in seawater electrolyte (Figure 3c)^[54].
It is still a question if these transition metal SACs are
competitive for industry-level current densities and if
they can be stable under alkaline seawater con It is still a question if these transition metal SACs are
competitive for industry-level current densities and if
they can be stable under alkaline seawater condition.
3.2 **Reaction Selectivity**
A wide potential window fo competitive for industry-level current densities and if
they can be stable under alkaline seawater condition.
3.2 Reaction Selectivity
A wide potential window for selective OER is one
of the highest priorities in designing

EDL
 ANTRE EXECTS ON THE CONSULTER CONTINUES. The **EDL**
 EXECTS ON THE CONSULTER CONSULTER CONSULTER CONSULTER CONSULTER THE CONSULTER CONSULTER CONSULTER CONSULTER (A) STREAM ON A CONSULTER ON BRIGATION OF THE CONSU EXERCT THE CONSERVATE ASSOCIATE ASSOCIATE ASSOCIATE ASSOCIATE AND MENALLY ASSOCIATE AND MENALLY AND Figure 3. Gallent parallel and the spanse of Ni-No and the party-bar and the party-bar and the spanse of Ni-No and High correlation of Ni-No and High correlation is adapted surface anity correlation from ref^{le}. Copyri **IFigure 3**
 Figure 3 General strategies for boosting HER. (a) Structure of Ni-MoN and long-term durability for alkaline seawater electrolysis.

Adapted with permission from ref⁸¹⁹, Copyright 2022, Wiely-VCH. (b) Illu **Figure 3** General strategies for boosting HER. (a) Structure of Ni-MoN and long-term durability for alkaline sea
Adapted with permission from ref¹⁸⁹. Copyright 2022, Wiley-VCH. (b) Illustration of the hydronium ion gen **Figure 3** General strangies for hoosing HFF. (a) Shuteure of Ni-Mo and long-term durability for allatine searcts releaving the strangies of hoosing and strangies for hoosing the Real strangies (Ni-SN@C). HD1.: electric d Adapted with permission from re^{net}. Coyingly 2022, Wiley-VCH. (b) llhareation of the hydroniarion orelanesinon mechanismin of suitable surface miride curity down in experiment in the solution of the solution of the solu meter surface ambit (NisoNego', D.D.: esterne couse usyr. Analye Wilh permission from rer^{ou}. Copyright 2021,
Wiley-VCH. (c) Schemias of Ni-N, and the Gibbs free energy diagram of HER on the Ni-N, and Ni-N, configuration erative to the solution of the solution of the section and the set and performance of active temperature of the control of the section layers can be used not only as active layer of manganese oxide electrodeposited on IrO standard manipulation is the second of the second of the second and performance of protection layers. The species (second the properation layers and active enter, but also as anticorrosion layers. Based on the proven usef and the comparison of the comparison of the comparison and the procedure of the protection layer, Kuang et al. demon-

and the proven useful in restraining the correction layer, Kuang et al. demon-

ITO, active sites (Fig species (SeO₃⁻ and SeO₄⁻)^[55], which have attributed to newly formed layers can be used not only as active layer of manganese oxide electrodeposited on IrO, is
center, but also as anticorrosion layers. Based on the proven useful in restraining the corrosion of Cl⁻ on
perspec newly formed layers can be used not only as active

exerter, but also as anticorrosion layers. Based on the

perspective of protection layer, Kuang et al. demon-

IrO, active sites (Figure 4G

strated a multilayer electro center, but also as anticorrosion layers. Based on the proven useful in restraining the corrosion of Cl⁻ on
perspective of protection layer R, kiange et al. denon-
In Acchimeter as and can be strained an multilayer el perspective of protection layer, Kuang et al. demon-

strated a multilayer electrode consisting of a Ni^{te} ductive carbon-based materials (e.g., layered carbon,

slayer deposited consisting of a Niete ductive carbon-base byproducts. er and NiS, layer deposited on the porous Ni foam. graphene, graphene oxide, and carbon nitride) on the amorphoso syxper-containing NiFe layer vas in catalyst surface lawe because the contract entergy to ci-
an generated

osting HER. (a) Structure of Ni-MoN and long-term durability for alkaline seawater electrolysis.
⁶⁾. Copyright 2022, Wiley-VCH. (b) Illustration of the hydronium ion generation mechanism on a
SN@C). EDL: electric double End to the state of the respectively a statice and the state at a many be used not only as active at proven useful in restraining the corrosion of Cl⁻ on
layer, Kuang et al. demon-
IrO, active sites (Figure 4c)^[56]. I ed layers can be used not only as active
layer of manganese oxide electrodeposited on IrO, is
sloo as anticonoroin layers. Based on the provon useful in restraining the corrosion of Cl⁻ on
of protection layer, Kuang et is on IrO_x active sites (Figure 4c)^[56]. In fact, coating conductive carbon-based materials (e.g., layered carbon, **EDL**
 EDL EDL

SNIQC

Fraction and long-term durability for alkaline seawater electrolysis.

b) Illustration of the hydronium ion generation mechanism on a

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ram of HER o **Example 11**
 these Conduct the conduct of the hydronium ion generation experience of the hydronium ion generation mechanism on a

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foN and long-term durability for alkaline seawater electrolysis.
Jo) Illustration of the hydronium ion generation mechanism on a
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In all ong-term durability for alkaline seawater electrolysis.

ayer: Adapted with permission from ref¹⁴⁹. Copyright 2021,

ayer: Adapted with permission from ref¹⁴⁹. Copyright 2021,

ram of HER on the Ni foN and long-term durability for alkaline seawater electrolysis.

b) Illustration of the hydronium ion generation mechanism on a

ayer. Adapted with permission from ref¹⁴⁹¹. Copyright 2021,

ram of HER on the Ni-N₃ an negatively charged surface can repulse the Cl⁻ ion. foN and long-term durability for alkaline seawater electrolysis.

b) Illustration of the hydronium ion generation mechanism on a

ayer. Adapted with permission from ref¹⁸⁹. Copyright 2021,

ram of HER on the Ni-N₃ and b) Illustration of the hydronium ion generation mechanism on a
sayer. Adapted with permission from ref¹⁸⁹. Copyright 2021,
ram of HER on the Ni-N₃ and Ni-N₄ configurations at pH = 14.
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layer of manganes ayer. Adapted with permission from ref¹⁹⁷¹. Copyright 2021,
ram of HER on the Ni-N₃ and Ni-N₄ configurations at pH = 14.
olor on line)
layer of manganese oxide electrodeposited on IrO₃ is
proven useful in restrain Figure 1.1 and the could effect the could effect the FeOOH and antiorrosion tective sites (Figure 4c)⁽⁵⁶⁾. In fact, coating conductive carbon-based materials (e.g., layered carbon, graphene, graphene oxide, and carbon n layer of manganese oxide electrodeposited on IrO, is
proven useful in restraining the corrosion of CI⁻ on
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IrO, active sites (Figure 4c)^[56]. In fact, coating con-
ductive carbon-based materials (e.g., layered carbon,
graphene, graphene oxide, and carbon nitride) on the
 IrO, active sites (Figure 4c)^[56]. In fact, coating conductive carbon-based materials (e.g., layered carbon, graphene, graphene oxide, and carbon nitride) on the catalyst surface have been an effective strategy to eithe e sites (Figure 4c)^[56]. In fact, coating con-
trbon-based materials (e.g., layered carbon,
graphene oxide, and carbon nitride) on the
trface have been an effective strategy to ei-
the conductivity of electrode, or reta active carbon-based materials (e.g., layered carbon,
aphene, graphene oxide, and carbon nitride) on the
talyst surface have been an effective strategy to ei-
er boost the conductivity of electrode, or retain the
reformanc graphene, graphene oxide, and carbon nitride) on the
catalyst surface have been an effective strategy to ei-
ther boost the conductivity of electrode, or retain the
performance of active sites under harsh conditions
due t

 $\# \# \# (I. \n Electrochem.) 2022, 28(10), 2214006 (8 of 18)$

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general approach to enhance the structural stability of

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of seaw the $\#(\#(J. Electron) 2022, 28(10), 2214006 (8 of 18)$
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Different from anodic OER, the primary concern
for cathodic HER relates to the precipitates. As we
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Different from anodic OER, the primary concern
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seawater contains high concentrati 2, 28(10), 2214006 (8 of 18)
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Different from anodic OER, the primary concern
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Different from anodic OER, the primary concern

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Example 18
 EXAMORE CONDEMISTER A EXAMORE ADOXED ADOXED ADOXED ADOXED ADOXED ADOXED ADOXED ADOXED HER, it is necessary to inhibit th

hanced anticorrosion ability (Figure 5b), adopting

guarantecing the mass transport rates. Thus, such a

studiole ion exchange membrane to protect the clee-

trocalalyst from the corrosive seawater (Figure 5c), or

1000 m suitable ion exchange membrane to protect the cles-

troceatalys for the corrections from the corrections seawerer (Figure 5.6), r 1000 mA · cm² at the ultral
voi vectpodential of 325

using permselective barrier layers trocatalyst from the corrosive seawater (Figure 5e), or $1000 \text{ mA} \cdot \text{cm}^{-2}$ at the ultralow overpotential of 325
using permselective barrier layers attached onto the mV. Furthermore, Seenivasan et al. developed a more
c using permselective barrier layers attached onto the mV. Furthermore, Seenivasan et al. developed a more considered effective methods to promote the long-
considered effective methods to promote the long-
different interfa cathode materials, blocking adverse reactions are complicated NiCo₅S/NiMo₅S/NiO electrodewith two considered effective methods to promote the long-
inter duratbility of seawater HER (Figure 5d). eurs on the surface rec considered effective methods to promote the long-

infferent interfaces^[76]. The OER process actually oc-

3.3 Mass Transfer

time durability of seawater HER (Figure 5d),

some use on the surface reconstructed MOOH and s time durability of seawater HFR (Figure 5d).

21.3 Mass Transfer

23. Mass Transfer

25. Mass Transfer because the break the M-S sites. This catalys showed superior

5 Senwater cletrolysis performance at high current

mec

Example 1988

Example 1888 Transformations of properties and potential solutions for promoting selectivity of HR in seawate. (a) Flectrode corresion by CI ions and

deposition of precipiates on active sites. (b) Electro **EXERENT And Considered Exerces CONSIDENT CONSIDERATION**
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 Example 1.1 Alloyed Cathods

Alloyed Cathods
 EXECTE CONFIGURE: Controllar Seamannial solutions for promoting selectrivity of HER in seawater. (a) Electrode corrosion by C1 ions and

cosition of precipitates on active sites, (b) Electrode alloying engineering, (c) regues channels as material solution of pointing selectively in rink in seasonate clay reactions and dependent of proposition of precipitates on active sites. (b) Electrole alloying empineering, (c) employment of ion exch Expansion to the mass transfer to the matter of the mass transfer rate (s) or the mass transfer rate and the matter of the detection of th HFR, it is necessary to inhibit the unfavorable elec-

figuration¹⁹²! In these catalysts, the porous morpholo-

trochemical reaction. According to this design princi-

gy of NiS nanosheets contributed to the efficient i HER, it is necessary to inhibit the unfinorable elec-
figuration⁷⁹¹. In these catalysts, the porous morpholo-
trochemical reaction. According to this design princi-
ple, developing alloyed electrocatalysts with an en-
t IFIR, it is necessary to inhibit the unfivorable elec-

froguencion²³¹. In these catalysts, the porous morpholo-

trochemical reading to this design princi- gy of NiS nameshees contributed to the efficient infil-

ple, trochemical reaction. According to this design princi-

gy of NiS nanosheets contributed to the efficient infil-

ple, developing alloyed electrocatalyst with an en-

traino of electrolyte and the desorption of D₃ bubles ple, developing alloyed electrocatalysts with an en-

hand cateorrosion ability (Figure 5b), adopting guarantecing the mass transport rates. Thus, such a

suitable ion exchange membrane to protect the clec-

Nife LDH/NiS NiFe LDH/NiS system delivered a current density of Ca²² Mg²² Pb²² C_U²² C_U² C_U² C_U² C_U² C_U² C_U² C_U Pb²⁺ Cu²⁺

Permselective layer

Alloyed Cathode

ter. (a) Electrode corrosion by Cl⁻ ions and

the ultralow overhange membrane, and (d)

the ultralow overpotential of 325

the ultralow overpotential of 325

e, Seeni Ca²⁺

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Permselective layer

Alloyed Cathode

By of HER in seawater. (a) Electrode corrosion by Cl⁻ ions and

ineering, (c) employment of ion exchange membrane, and (d)

or on line)

figuration^[75]. In t **Example 18 Alloyed Cathode**

Fermselective layer

Alloyed Cathode

y of HER in seawater. (a) Electrode corrosion by Cl⁻ ions and

innering, (c) employment of ion exchange membrane, and (d)

figuration^[75]. In these c **Example 18**

Fermselective layer

Alloyed Cathode

Ny of HER in seawater. (a) Electrode corrosion by Cl⁻ ions and

innering, (c) employment of ion exchange membrane, and (d)

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figuration^[75]. In these cat **EXECUTE ALSO ASSET AND**

Fermselective layer

Alloyed Cathode

thereing, (c) employment of ion exchange membrane, and (d)

figuration¹⁷⁵¹. In these catalysts, the porous morpholo-

figuration¹⁷⁵¹. In these catalysts, Alloyed Cathode

y of HER in seawater. (a) Electrode corrosion by Cl⁻ ions and

intering, (c) employment of ion exchange membrane, and (d)

or on line)

figuration^[75]. In these catalysts, the porous morpholo-

gy of by of HER in seawater. (a) Electrode corrosion by CI-ions and
ineering, (c) employment of ion exchange membrane, and (d)
or on line)
figuration^[75]. In these catalysts, the porous morpholo-
gy of NiS nanosheets contribu is ty of HER in seawater. (a) Electrode corrosion by CF ions and
ineering, (c) employment of ion exchange membrane, and (d)
or on line)
figuration^[75]. In these catalysts, the porous morpholo-
gy of NiS nanosheets contr metalling, (c) employment of one exchange memoiane, and (d)
or on line)
figuration^[75]. In these catalysts, the porous morpholo-
gy of NiS nanosheets contributed to the efficient infil-
tration of electrolyte and the de A low interface constrained to the energy of the catalysts, and α detection of Calcordic and the description of O₂ bubbles, aranteeing the mass transport rates. Thus, such a Fe LDH/NiS system delivered a current dens figuration^[75]. In these catalysts, the porous morphology of NiS nanoshects contributed to the efficient infiltration of electrolyte and the desorption of O₂ bubbles, guaranteeing the mass transport rates. Thus, such figuration^[75]. In these catalysts, the porous morphology of NiS nanosheets contributed to the efficient infiltration of electrolyte and the desorption of O₂ bubbles, guaranteeing the mass transport rates. Thus, such gy of NiS nanosheets contributed to the efficient infil-
tration of electrolyte and the desorption of O₂ bubbles,
guaranteeing the mass transport rates. Thus, such a
NiFe LDH/NiS system delivered a current density of
10 tration of electrolyte and the desorption of O₂ bubbles,
guaranteeing the mass transport rates. Thus, such a
NiFe LDH/NiS system delivered a current density of
1000 mA \cdot cm⁻² at the ultralow overpotential of 325
mV. guaranteeing the mass transport rates. Thus, such a
NiFe LDH/NiS system delivered a current density of
1000 mA \cdot cm⁻² at the ultralow overpotential of 325
mV. Furthermore, Scenivasan et al. developed a more
complicate

NiFe LDH/NiS system delivered a current density of 1000 mA \cdot cm⁻² at the ultralow overpotential of 325 mV. Furthermore, Seenivasan et al. developed a more complicated NiCo₂S₄/NiMo₂S₄/NiO electrodewith two diff 1000 mA \cdot cm⁻² at the ultralow overpotential of 325 mV. Furthermore, Seenivasan et al. developed a more complicated NiCo₂S₄/NiMo₂S₄/NiO electrodewith two different interfaces^[76]. The OER process actually oc mV. Furthermore, Seenivasan et al. developed a more
complicated NiCo₂S₄/NiMo₂S₄/NiO electrodewith two
different interfaces^[76]. The OER process actually oc-
curs on the surface reconstructed MOOH and surface
ben complicated NiCo₂S₄/NiMo₂S₄/NiO electrodewith two
different interfaces^{$[76]$}. The OER process actually oc-
curs on the surface reconstructed MOOH and surface
beneath the M-S sites. This catalyst showed superior
 different interfaces^[76]. The OER process actually oc-
curs on the surface reconstructed MOOH and surface
beneath the M-S sites. This catalyst showed superior
mechanical strength and high density of active sites,
and co curs on the surface reconstructed MOOH and surface
beneath the M-S sites. This catalyst showed superior
mechanical strength and high density of active sites,
and consequently, good industrial durability and re-
action kine

OH⁻ ions are formed at the cathode under electrolysis considered for the industrial operation.
 4 Industrial Electrolyzer for Direct remembrane electrole assembly and bity, the converted assembly and the electrolyzion of the membrane electrole assembly and bity. We first b sis technologies, considering the technical evolution

eration, acidic water is pumpel into the ande

electrolyzer can be divided into three categories. Currently, the common

electrolyzer can be divided into three catego

Considered for the industrial of established electrolysis

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The industrial operation of the 1981 This method is the state of the considered to the method of the method of the state of CP Ni foam Pt foil PVNi-Mo C -2000

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By dynamic contact angle hysteresis images of electrolyte drop on different substrates, (c) Comparation of the

Season inc **EXECUTE ANTEL THE CONDUPERTY CONDUPED THE CONDUPERTY (CONDUPERTY AND A CONDUPERTY (ACT) (CONDUPERTY (Colorom line contact ungle hysteresis images of electrolyte drop on different substrats, (c) Comparation of polarizatio Figure 6** PtNi-Mo electroculalyal for enhanced mass transfer and calabylic performance. (a) Photographs of the static contact angles, and (b) dynamic contact angles, such as Etticon, considering the technical evolution i and (b) dynamic contact angle hyderesis images of electrolye drop on different substrates. (c) Comparation of polarization curves
with 85% it compensation for different estatysts in simulated seawater. Adapted with permiss with 85% iR compensation for different catalysts in simulated seawater. Adapted with permission from nef^{tra}, Copyright 2021, Wi-
toy-VCH, (color on line)

trode surface. As a result, this catalyst exhibited a

mphragm m ley-VCII. (color on line)

trode surface. As a result, this eatalyst exhibited a aphragm materials, such as Zirfon, are approved

high-level current density of 2000 mA·cm⁻ at an ul-

physically robust, allowing both anio trode surface. As a result, this catalyst exhibited a aphragm materials, such as Zirfon, are approved
thigh-level current density of 2000 mA - cm^{-a} at an ul-
physically robust, allowing both anions and cations,
tralow o trode surface. As a result, this catalyst exhibited a aphragm materials, such as Zirfon, are approved
thigh-level current density of 2000 mA·cm⁻² at an ul-
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state of the cost-energy of 2000 matrices and cost-energy of the difference cost-energy of the matrices
of the cost-energy of the same-alkaline such as Hr, Na', OH^T and Cl', to pass t From the same of the realm-antamic scale and corresponding in the same of the real industrial-scale hydrogen in the real industrial-scale durability (Figure 6c). It is believed that such structure ions and decrease the o etectrolyge, samowing exenterative and operation and perfectrol and the this detectrolygies of the simulation of t durability (Figure 6c). It is believed that such structure

ions and decrease the overally worth on AF technologies,

exonsidered for the industrial operation.
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 4 ing or emnear earliers around the generality. Some sculpture through the cathod of the cathodical methanic cathod at the cathodic distribution of the cathodic distribution of the cathodic methanologies, considering the el increased in the content
angle to the membrane electrode assembly and bipolar plates
(Figure 7b), and are characterized by high current
density, operation efficiency, and tolerance to fluctu-
the established electroly-
an **4 Industrial Electrolyzer for Direct**
 Solution (Figure 7b), and are characterized by high current
 Selution (Figure 7b), and are characterized by high current

six elembologies, considering the technical evolution
 Seawater Electrolysis

Vergite η , denote the established electroly-

we first briefly introduce the established electroly-

interaction of Chicaretis sixtendiogies, considering the technical evolution

and censoring We first briefly introduce the established electroly

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sing currents of renewable electricity. During the co-

sing currents of renewable electricity. During the op-
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s $\begin{bmatrix}\n\mathbf{2} & \mathbf{1} \\
\mathbf{3} & \mathbf{1}\n\end{bmatrix}$ Example 1000

The transference rate of the state contact angles

The transference rate of the state contact angles

on different substrates. (c) Comparation of polarization curves

there. Adapted with permission from ref Figure 1000

Figure 3-1000

Figure 3-2000

The overpotential (V)

Comparison for the static contact angles,

on different substrates. (c) Comparation of polarization curves

tuer. Adapted with permission from ref¹¹³. Co to poor selectivity. Different and the control of the selectivity operator and decrease (c) Comparation of polarization curves
the Adapted with permission from ref¹²¹. Copyright 2021, Wi-
applying the static contact ang Electrolyzer (PEME)

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on different substrates. (c) Comparation of polarization curves

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Overpotential (V)
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Overpotential (V)

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tter. Adapted with permission from ref^[13]. Copy talytic performance. (a) Photographs of the static contact angles,
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aphragm materials, such as talytic performance. (a) Photographs of the static contact angles,
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aphragm materials, such as on different substrates. (c) Comparation of polarization curves
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aphragm materials, such as Zirfon, are approved
physically robust, allowing both anions and ration curves
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aphragm materials, such as Zirfon, are approved
physically robust, allowing both anions and cations,
such as H⁺, Na⁺, OH⁻ and Cl⁻, to pass through^{[7} aphragm materials, such as Zirfon, are approved
physically robust, allowing both anions and cations,
such as H⁺, Na⁺, OH⁻ and Cl⁻, to pass through^[78]. This
may lower the transference rate of the most mobile
ion aphragm materials, such as Zirfon, are approved
physically robust, allowing both anions and cations,
such as H⁺, Na⁺, OH⁻ and Cl⁺, to pass through^[78]. This
may lower the transference rate of the most mobile
ion aphragm materials, such as Zirfon, are approved
physically robust, allowing both anions and cations,
such as H', Na', OH⁻ and Cl', to pass through^[78]. This
may lower the transference rate of the most mobile
ions and physically robust, allowing both anions and cations, physically robust, allowing both anions and cations, such as H', Na', OH⁻ and Cl⁻, to pass through^[78]. This may lower the transference rate of the most mobile io pyrixany. The star and general control and Bulletin and SH', Na', OH' and CI', to pass through^[78]. This may lower the transference rate of the most mobile ions and decrease the overall working efficiency due to poor se may lower the transference rate of the most virtual or may lower the transference rate of the most mobile ions and decrease the overall working efficiency due to poor selectivity. Different from AE technologies, a PEM ele ronment and anticrocordinate that we have the most most most most moderate the operall working efficiency due to poor selectrolyzer (PEME) generally consists of a membrane electrode assembly and bipolar plates (Figure 7b) to boot selectivity. Different from AE technologies,
a PEM electrolyzer (PEME) generally consists of a
membrane electrodyzer (PEME) generally consists of a
membrane electrode assembly and bipolar plates
(Figure 7b), and a water into the cathode compartment, H_2 and OH⁻ ions a per society, \overline{P} constants nont and \overline{P} consists of a
a per sectionly \overline{P} (FEME) generally consists of a
membrane electrode assembly and bipolar plates
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OH⁻ ions
ions pass
in \sim The vactory exchange membrane and the anomorphase or

anomhana electrode assembly and bipolar plates

(Figure 7b), and are characterized by high current

density, operation efficiency, and tolerance to fluctu-

ating curr through the AEM into the anode, evolving into $O_2^{[11]}$. The AEM incording the controllary and α point planes.
(Figure 7b), and are characterized by high current density, operation efficiency, and tolerance to fluctuating currents of renewable electricity. During the operati (v_{L} gare 7*i*), and are vanatured to y mg/c vanishing density, operation efficiency, and tolerance to fluctuating currents of renewable electricity. During the operation, acidic water is pumped into the anode half-c stration, potention constents, the controllating currents of renewable electricity. During the operation, acidic water is pumped into the anode half-cell to be oxidized into O_2 and the H⁺ ions transfer to the cathode eration, acidic water is pumped into the anode half-cell to be oxidized into O_2 and the H⁺ ions transfer to the cathode to evolve into H₂ through the PEME. Generally, PEME is conducted under corrosive acidic condit

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economic benefits^[79]. Figure 7d is the photograph and

tions, seawater should be treated with negative pres-

fine schem economic benefits^[79]. Figure 7d is the photograph and
tions, seawater should be treated with negative pres-
fine schematic of a commercial PEME electrolysis sure filter to remove large-sized impurities, followed
cell¹ economic benefits^[79]. Figure 7d is the photograph and

tions, seawater should be treated with negative pres-

fine schematic of a commercial PEME electrolysis sure filter to tremove large-sized impurities, followed

ece fine schematic of a commercial PEME electrolysis sure filter to remove large-sized impurities, followed cell¹⁸¹. The membrane stack is assembled by two IIER **b** and the purification step via reverse osmosis cells on the cell⁰³. The membrane stack is assembled by two HER by a further purification step via reverse osmosis cells on the end sides and two OER cells in malled in (RO) and other purification strategies (Figure 8a). And the unid cells on the end sides and two OER cells installed in (RO) and other purification
the middle. The AEM separates the HER cells and Another feasible way to r
OER cells to prevent gas diffusion and allow anions membrane perf the middle. The AEM separates the HER cells and

one-the reasible way to maintain the exchange

OER cells to prevent gas diffusion and allow anions membrane performance is through the designed re-

or to transfer through. OFR cells to prevent gas diffusion and allow anions

membrane performance is through the designed re-

torials for totals of clectrolyzers are totals components. For instance, periodi rest of clear-

when the above three to transfer through. covery operations. For instance, periodic rest of electrolyzes are

When the above three kinds of electrolyzers are urby
correlations are dependently deployed for direct seawater electrolysis, some ne

He above the above the process of the above the section of the above the above through the above that the above that the above that is adapted with permission from ref^{ta}. Copyright 2021, Wiley-YCH, (cl) photon exchange m **Example 18**
 Example 7 Typical configurations for water electrolyzes, Schematic of (a) allealine exchange membrane

value relectrolyzer (PEME), and (c) union exchange membrane water electrolyzer (AEME), (a) Photograph Example and the station and electrolytics. Schematic of (a) alkaline exchange membrane

Figure 7 Typical configurations for water electrolytzers. Schematic of (a) alkaline electrolytzer (AF), (b) proton exchange membrane
 Example 19:
 Example Symbox
 Example Symbox Solution Askaine electrolyzer, (AE), (b) proton exchange membrane

water electrolyzer (PEME), and (c) anion exchange membrane water electrolyzer (AE). (d) Photograph and s **Figure 7** Typical configurations for water electrolyzers. Schematic of (a) alkaline electrolyzer (AE), (b) proton exchange membrane water electrolyzer (PFMF), and (c) anion exchange membrane water electrolyzer (PFMF), an **Eigner 7** Typical condigurations for water electrolyzer (*PHS*). And (so il also also the electrolyzer (AFME). (AD, (b) proton exchange membrane of all and proton exchange membrane of an PEME. Panel d is adapted with per water electrolyzer (PEME), and (c) anion exchange membrane water electrolyzer (AEME). (d) Photograph and schematic of an

ECME. Panel d is adapted with permission from ref¹⁰. Copyright 2021, Wiley-VCH. (color on line)

e Anode

Anode

Another feature of the flux of the flux of the flux of the distance exchange membrane

(a) alkaline electrolyzer (AEME). (b) proton exchange membrane

(e) a such a such the exchange membrane

(e) and other p Anode

M₂O flow

Alkaline exchange membrane

(a) alkaline exchange membrane

(re-lectrolyzer (AEME). (d) protograph and schematic of an

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tions, scawater should be treated with negative pre Cathode

(A) flow

Alkaline exchange membrane

(a) alkaline electrolyzer (AEME). (b) proton exchange membrane

ter electrolyzer (AEME). (d) Photograph and schematic of an

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tions, seawater sh Cathode

H₂O flow

Alkaline exchange membrane

(f (a) alkaline electrolyzer (AE), (b) proton exchange membrane

ter electrolyzer (AEME). (d) Photograph and schematic of an

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H₂O flow

Alkaline exchange membrane

f(a) alkaline electrolyzer (AE), (b) proton exchange membrane

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H₂O flow

Alkaline exchange membrane

f (a) alkaline electrolyzer (AE), (b) proton exchange membrane

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tions, seawater H₂O flow
 Alkaline exchange membrane

f(a) alkaline exchange membrane

re relectrolyzer (AEME). (d) Photograph and schematic of an

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tions, seawater should be treated with negative pres-
 a) alkaline electrolyzer (AE), (b) proton exchange membrane
electrolyzer (AEME). (d) Photograph and schematic of an
Wiley-VCH. (color on line)
ons, seawater should be treated with negative pres-
reference filter to remove f (a) alkaline electrolyzer (AE), (b) proton exchange membrane
re electrolyzer (AEME). (d) Photograph and schematic of an
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tions, seawater should be treated with negative pres-
sure filter to ier electrolyzer (AEME). (d) Photograph and schematic of an
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tions, seawater should be treated with negative pres-
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tions, seawater should be treated with negative pres-
sure filter to remove large-sized impurities, followed
by a further purification step via reverse osmosis
(RO) and other purification stra tions, seawater should be treated with negative pressure filter to remove large-sized impurities, followed by a further purification strong via reverse osmosis (RO) and other purification strategies (Figure 8a). Another fe tions, seawater should be treated with negative pressure filter to remove large-sized impurities, followed by a further purification step via reverse osmosis (RO) and other purification strategies (Figure 8a). Another feas

and sides and two OFR cells installed in (RO) and other purification strategies (Figure 8a).

Another feasible way to maintain the exchange

prevent gas diffusion and allow anions membrane performance is through the desig sure filter to remove large-sized impurities, followed
by a further purification step via reverse osmosis
(RO) and other purification strategies (Figure 8a).
Another feasible way to maintain the exchange
membrane performan by a further purification step via reverse osmosis
(RO) and other purification strategies (Figure 8a).
Another feasible way to maintain the exchange
membrane performance is through the designed re-
covery operations. For i (RO) and other purification strategies (Figure 8a).
Another feasible way to maintain the exchange
membrane performance is through the designed re-
covery operations. For instance, periodic rest of elec-
trolyzer at open c Another feasible way to maintain the exchange
membrane performance is through the designed re-
covery operations. For instance, periodic rest of elec-
trolyzer at open circuit has been applied to partially
recover the los membrane performance is through the designed re-
covery operations. For instance, periodic rest of elec-
trolyzer at open circuit has been applied to partially
recover the lost activity because of chloride trapped
in the e covery operations. For instance, periodic rest of electrolyzer at open circuit has been applied to partially recover the lost activity because of chloride trapped in the exchange membrane^[89]. But this will increase the periodic rest of elec-

applied to partially

e of chloride trapped

But this will increase

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which may lead to

ast, due to the proton

increase accordi

 $# \&L \# (J. \n *Electrochem.*) 2022, 28(10), 2214006 (12 of 18)$ is only about 6.4 mmol after standardized long-time gy. Considering that the planet's oceans

operation. Such a low Cl⁻ concentration minimizes most unlimited quantit bility.

 $\exists x \in \mathbb{R}$ is only about 6.4 mmol after standardized long-time

is only about 6.4 mmol after standardized long-time

operation. Such a low Cl⁻ concentration minimizes

corrosion to the anode material, and endows seaw $\pm \frac{\text{ln} \cdot \text{ln} \cdot \text{ln} \cdot \text{ln} \cdot \text{ln} \cdot \text{ln}}{1 - \text{ln} \cdot \text{ln} \cdot \text{ln} \cdot \text{ln}}}$

r standardized long-time gy. Considering that the planet's oceans supply al-

concentration minimizes gy. Considering that the planet's oceans s $\frac{d}{dx}$ (*L Electrochem.*) 2022, 28(10), 2214006 (12 of 18)

is only about 6.4 mmol after standardized long-time

gy. Considering that the planet's oceans supply al-

operation. Such a low Cl⁻ concentration minimize $\frac{d}{dt}\mathcal{L}^{\#}(J. Electron) \cdot 2022, 28(10), 2214006 \cdot (12 \text{ of } 18)$

is only about 6.4 mmol after standardized long-time

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operation. Such a low Cl⁻ concentration minimizes

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eration. Such a low Cl⁺ concentration mimimizes most unlimited quantities of 'seawater, which ac-
rosion to the anode material $\pm \frac{1}{2}E_{\pm} + \frac{1}{2}E_{\pm} + E_{\pm} + E_{\pm}$

is only about 6.4 mmol after standardized long-time

is in the planet's oceans supply al-

operation. Such a low Cl⁻ concentration minimizes most unlimited quantities of seawat ± 0.022 , ± 0 E/E-L (*Electrolem*, 2022, 28(10), 2214006 (12 of 18)
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operation. Such a low Cl⁻ concentration minimizes most un tyle \mathcal{L}_2 (*L Electrochem.*) 2022, 28(10), 2214006 (12 of 18)

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operation. Such a low C1⁻ concentration min electrolysis (150 ~ 400 ^oC) and solid oxide electroly- $\frac{\ln(k\pi\gamma_L \, k\text{Jecrow-bem.}}{1000}$ 2022, 28(10), 2214006 (12 of 18)

is only about 6.4 mmol after standardized long-time

gy. Considering that the planet's oceans supply al-

operation. Such a low CI - concentration minimize **EVALUATION** EVALUATION (12 A 16 A steam is only about 6.4 mmol after standardized long-time gy. Considering that the planet's occurs supply al-
operation. Such a low C1 concentration minimizes most unlimited quantities o **EVALUATION** EVALUATION (12 at 189)

is only about 6.4 mmol after standardized long-time

gy. Considering that the planet's oceans supply al-

operation. Such a low C1⁻ concentration minimizes most unlimited quantities *lectrochem.*) 2022, 28(10), 2214006 (12 of 18)

long-time gy. Considering that the planet's oceans supply al-

minimizes most unlimited quantities of seawater, which ac-

seawater counts for 96.5% of the total water reso $\frac{u_0}{dx}$ $\frac{u_1}{dx}$ $\frac{u_2}{dx}$ $\frac{u_3}{dx}$ $\frac{u_4}{dx}$ $\frac{u_5}{dx}$ $\frac{u_5}{dx}$ $\frac{u_6}{dx}$ $\frac{u_7}{dx}$ $\frac{u_8}{dx}$ $\frac{u_9}{dx}$ $\frac{u_9}{dx}$ $\frac{u_1}{dx}$ $\frac{u_1}{dx}$ $\frac{u_2}{dx}$ $\frac{u_3}{dx}$ $\frac{u_5}{dx}$ $\frac{u_6}{dx}$ $\frac{u$ is only about 6.4 mmol after stream securities are served and the planet's occurs supply al-
operation. Such a low C1⁻ concentration minimizes and costed in the planet's occurs supply al-
operation. Such a low C1⁻ con is only about 6.4 mmol after standardized long-time

operation. Such a low C1⁻ concentration minimizes most unlimited quantities of seawater, which ac-

occurrection minimizes most unlimited quantities of seawater with operation. Such a low C1⁻ concentration minimizes most unlimited quantities of seawater, which ac-
orison to the anode material, and endows seawater comus for 96.5% of the total water resources on the
electrolyzer with corrosion to the anode material, and endows seawater counts for 96.5% of the total water resources corrosion to the endoter
by electrolyzer with high selectivity and operation standary emplication stress
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ity.

terolyzer with seawater will reduce

Moreover, high-temperature water electrolyzer

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TE) has drawn broad atte chility.

Moreover, high-temperature water electrolyzer

Moreover, high-temperature water electrolyzer

marines. In this short review, we try to figure out the
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possibilit Moreover, high-temperature water electrolyzer

mewapplication avenues such as cargo ships and sub-

(HTE) has drawn broad attention as it offers signifi-

marines. In this short review, we try to figure out the

verticoma 2, 28(10), 2214006 (12 of 18)
gy. Considering that the planet's oceans supply al-
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工业级碱性海水电解:近期进展和展望

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摘要: 由太阳能、风能和海洋等可再生能源驱动的工业级水分解产氢为能源和环境的可持续性发展开辟了一条 极具潜力的道路。然而,在工业上最先进电解技术使用高纯水作为氢源,这这将带来严重的淡水资源危机。海水 分解为饮用水短缺提供了一条切实可行的解决途径,但仍面临规模工业化生产的巨大挑战。在这里,我们总结 了海水分解的最新进展,包括反应机制、电极设计标准和直接海水分解的工业电解槽。深入讨论了应对海水电 解中的关键挑战,如活性位点、反应选择性、耐腐蚀性和传质能力等的解决方案。此外,该文章重点总结了海 水电解设备的最新发展,并提出了设计长寿命直接海水电解装置的有效策略。最后,我们对直接海水电解的未 来机遇和挑战提出了自己的观点。

关键词: 海水电解:抗腐蚀设计:电极设计标准:工业电解槽