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# Alkaline Water Electrolysis for Efficient Hydrogen Production

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Wen-Fu Xie, Ming-Fei Shao\*<br> *Exhemical Resource* (State Key Laboratory of Chemical Resource Engineering, College of Chemistry,<br>  $\text{BUSL}^2(\text{SUSL}) = \frac{1}{2} \sum_{k=1}^{N} \frac{1}{$ 

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Key Laboratory  $\begin{array}{ll} \text{d} \xi & \text{d} \xi & \text{d} \xi \\ \text{Reiroebm, 2022, 28(10), 2214008 (1 of 18)} \\ \text{D0E: 10, 13208j, electrodem, 2214008} & \text{Hity/dteetrochem, xmu, edu, cm} \\ \text{Alkaline Water Electrolysis for Efficient Hydrogen Production} \\ & \text{Wern-Fu Xic, Ming-Fci Shao'} \\ & \text{(State Key Laboratory of Chemical Resources Engineering, College of Chemistry, Beijing University of Chemical Technology, Beijing 100029, China)} \\ \text{Abstract: Hydrogen production from water electrobysis is a satisfiable and environmentally being strategy in comparison with this$ **Existent**<br> **Existent**<br> **Fourtherm. 2022. 28(10), 2214008 (1 of 18)<br>
<b>ERENGENT DESCALE HYDROGEN. THE EXECT DANS** of the suffered hydrogen. Production<br> **Alkaline Water Electrolysis for Efficient Hydrogen Production**<br>  $\frac{1$  $\frac{1}{2}$ <br> *L Electrochem. 2022, 28(10), 2214008 (1 of 18)<br> [Review] DOI: 10.13208j electrochem.20214008<br> Alkaline Water Electrolysis for Efficient Hydrogen Production<br>
Ween-Fu Xic, Ming-Fei Shao<sup>t</sup><br>
(State <i>Key La* **Herican Marine Water Electrolysis for Efficient Hydrogen Production**<br> **Alkaline Water Electrolysis for Efficient Hydrogen Production**<br>  $\frac{1}{2}$  (*State Key Laboratory of Chemical Resource Engineering, College of Chemist* Examples: We are the controlled at the source Engineering, College of Chemistry,<br>
(State Key Laboratory of Chemical Resource Engineering, College of Chemistry,<br>
Beijing University of Chemical Resource Engineering, College Wen-Fu Xie, Ming-Fei Shao<sup>7</sup><br>
(State Key Laboratory of Chemical Resource Engineering, College of Chemistry,<br>
Reijing University of Chemical Resource Engineering, College of Chemistry,<br>
Reijing University of Chemical Techno (Sidde Key Laboratory of Chemical Resource Engineering, College of Chemistry,<br>
Beijing University of Chemical Technology, Beijing 100029, China)<br> **Abstract:** Hydrogen production from water electrolysis is a sustainable an **Example 1**<br> **Example 1** *Belging University of Chemical Technology, Beijing 100029, China)*<br> **Abstract:** Ifydogen production from water electrolysis is a sustainable and environmentally benign strategy in comparison with<br> **Abstract:** Hydrogen production from water electrolysis is a sustainable and environmentally benign strategy in comparison with<br>
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fossil fuel-based hydrogen. However, this promising technique suffers from the high energy co **Abstract:** Hydrogen production from water electrolysis is a sustainable and environmentally benign strategy in comparison with<br>fossil firel-based hydrogen. However, this promissing technique suffers from the high energy fossil fitel-based hydrogen. However, this promising technique suffers from the high energy consumption and unsatisfactory cost<br>that a timely and comprehensive review on and variety stability of electrocatalysts. To addet Ming-Fei Shao<sup>\*</sup><br>
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1 Introduction cation being the most dominant approaches, which

energy conversion and carbon neutrality with the electrictly is attracting growing interest to produce<br>emission, and high efficiency<sup>5</sup>.<sup>21</sup>, The overall hydrogen mental-friendly and feasibility of largescale produc-<br>energ between the high-purity consumption and unsatisfactory cost<br>of electrocatalysts. To address this challenge, herein, we pre-<br>relectrolysis that is already commercialized for large scale hy-<br>g to promote the performance of h poten of electrocatalysts. To address this challenge, herein, we pre-<br>relectrolysis that is already commercialized for large scale hy-<br>g to promote the performance of hydrogen generation are dis-<br>m. The challenges and rela is relativelys that is already commercialized for large scale hy-<br>
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ion of hydrogen production.<br> g to promote the performance of hydrogen generation are dis-<br>em. The challenges and related prospects are presented at last,<br>ion of hydrogen production.<br>electrode; coupled reaction<br>cation being the most dominant approaches from The challenges and related prospects are presented at last,<br>
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The background, the pressure is solvent and a state in AWE. Comprehensive comparisons of AWE, PEMWE solve is the<br>
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 $\frac{\text{#}\{\&\cong\}(L \text{~Electrochem.})\ 2022, 28(10), 2214008\ (4 of 18)}{\text{Donitz in } 1980s, respectively (Figure 3a)^{(31)}. And the  
development of appropriate electrocatalysts with suit-  
gle-atom catalysts (SACs) have shown great promise  
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in water electrolysis in recent years<sup>[83]</sup>. For instance,  
quired for water electrolysis. During the past few  
nitrogen-doped graphene nanosheets supported  
decades, numerous electrocatalysts, including noble  
Pr-SAC was fabricated by Sun and co-workers in  
metal, non-noble metal and metal-free electrocata-  
2$  $\pm \ell \ell \ddot{\mp} (J. Electrochem.) 2022, 28(10), 2214008 (4 of 18)$ Donitz in 1980s, respectively (Figure 3a)<sup>031</sup>. And the ciency and adjustable coordination structure, sin-<br>
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Donitz in 1980s, respectively (Figure 3a)<sup>131</sup>. And the ciency and adjustable coordination structure, sin-<br>
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development of appropriate electrocatalysts w  $\text{EPE}(L)$ . Electrochem.) 2022, 28(10), 2214008 (4 of 18)<br>
Donitz in 1980s, respectively (Figure 3a)<sup>101</sup>. And the ciency and adjustable coordination structure, sin-<br>
development of appropriate electrocatalysts with suitthe  $2(1.60)$  that  $2(1.60)$  the strengthenul  $2(2.2 \times 100)$ ,  $2(14008 (4 of 18))$ <br>
Donitz in 1980s, respectively (Figure 3a)<sup>331</sup>. And the ciency and adjustable coordination structure, sin-<br>
development of appropriate electr the  $\mathcal{C}_2$  methals for HER in 2005 via analyzing the relation-<br>
the exchange and condination structure, since<br>
development of appropriate electrocatalysts with suit-<br>
gle-atom catalysts (SACs) have shown great promise<br> **EVALUATION**<br> **EVALUATION**<br> **EXECUTE:** THENG, respectively (Figure 3a)<sup>191</sup>! And the ciency and adjustable coordination structure, sim-<br>
Development of appropriate electrocetallysts with suit-<br>
gle-atom catalysts (SACs) h **HER, 1998** (*Electrocalems*) 2022, 28(10), 2214008 (4 of 18)<br>
Domitz in 1980s, respectively (Figure 3a)<sup>281</sup>. And the circley and adjustable coordination structure, sin-<br>
development of appropriate electrocalaylys with s  $\frac{1}{2}$  ( $\frac{1}{2}$  ( $\frac{1}{2}$   $\frac{1}{2}$  ( $\frac{1}{2}$   $\frac{1}{2}$ The  $t^2\mathcal{R}(L \tReemomen) 2022,28(10), 2214008 (4 of 18)$ <br>Donitz in 1980s, respectively (Figure 3a)<sup>191</sup>. And the ciency and adjustable coordination structure, sin-<br>development of appropriate electrocatalysts with suit-<br>given cat Donitz in 1980s, respectively Figure 2017 is an<br>elevelopment of appropriate electrocatalysts with suit-<br>elevelopment of appropriate electrocatalysts with suit-<br>elevelopment are not algorithms are not algorithms are not al Donitz in 1980s, respectively (Figure 3a)<sup>201</sup>. And the ciency and adjustable coordination structure, sin-<br>development of appropriate electrocatalysts with suit-<br> $q$  lect-atom catalysts (SACs) have shown great promise<br>abl development of appropriate electrocatalysts with suit-<br>
gle-atom catalysts (SACs) have shown great promise<br>
able physical and chemelical properties is highly re-<br>
in water electrocatalysts, During the past few introgen-do able physical and chemical properties is highly re-<br>
in water electrolysis in recent vearse<sup>150</sup>. For instance,<br>
duced or water electrocollysis, During the past few introgen-doped graphene manosheets supported<br>
decades, nu quired for water electrolysis. During the past few mitrogen-doped graphene nanosheets supported<br>decades, numerous electrocatistys, including noble PE-SAC was finiteedited by Sum and co-workers in<br>metal, non-noble metal an decades, numerous electrocatalysts, including noble<br>
metal, non-noble metal and metal-free electrocata-<br>
1991s with single-atom, nanocluster, nanoparticle and<br>
much high activity and stability for HFR than com-<br>
1991s wit metal, non-noble metal and metal-free electrocata-<br>
2016 by atomic layer deposition, which exhibited<br>
hyans with single-atom, nanoclaster, nanoclastic and much high activity and stability for HER than com-<br>
nanocaray stru lysts with single-atom, nanocluster, nanoparticle and<br>much high activity and stability for HER than com-<br>anaromy structure, have been widely explored for mercial PrC<sup>tail</sup>,<br>water electrolysis,<sup>[vi]</sup>. Stimming and co-worker nanoamy structure, have been widely explored for<br>mercial Pt/C<sup>130</sup>, savare electrolysis,<br>suledd that Pt is the better electroceatalyst than other<br>memoris electroceatalyst have shown promising ac-<br>electrocatalyst hand co-w water electrolysis<sup>[37]</sup>. Stimming and co-workers con-<br>
chided that Pi is the better electrolect cluded that Pt is the better electrocatalyst than other<br>metrics of ref. En 2005 via analyzing the relation-<br>this providing a complex ship between hydrogen chemisorption energies and<br>electrocatalyst developed by Nakamura a metals for HER in 2005 via analyzing the relation-<br>
inity and stability for HER. For example,  $\gamma$ -MnO<sub>2</sub><br>
ship between hydrogen chemisoprion omergies and<br>
cortocatalyst developed by Nakamura and co-work-<br>
enceptrocatalys ship between hydrogen chemisorption energies and<br>
electrocatalyst developed by Nakamura and co-work-<br>
the schange current of FIER, thus providing a theo-<br>
ereiction function for the subsequent development of<br>
hours<sup>163</sup> a the exchange eurrent of HER, thus providing a theo-<br>erise continuously for more than 8000<br>reliefal foundation for the subsequent of hereavies and evidy and PVNi-Mo electrocatalyst developed by<br>electrocatalyst for HER<sup>(3)</sup> retical foundation for the subsequent development of<br>electrocatalyst developed by<br>electrocatalyst for HER<sup>(m</sup>). Considering scarce and ex-<br>- Liu and co-workers realized an ultrahilp current den-<br>electrocatalyst for HER pe electrocatalyst for HFR<sup>181</sup>. Considering scarce and ex-<br>
Liu and co-workers realized an ultrahigh current den-<br>
pensive P group metals are not suitable for large sity of 2000 mA-cm<sup>3</sup> at an overpotential of 113 mV<sup>64</sup>,<br> pensive Pt group metals are not suitable for large sity of 2000 mA·cm<sup>-</sup> at an overpotential of 113 mV<sup>/ma</sup>,<br>scale applications, it is therefore crucial to find alter-<br>denominating the feasibility for practical vater elec scale applications, it is therefore crucial to find alter-<br>matrixes to the PI group chectrostatysts. Through den-<br>matrixes to the PI group correcteatlysts, Through density of the and co-workers prenared a<br>misy fonetional t natives to the Pt group electrocetal<br>systs. Through den-<br>stiy functional theory (DFT) calculations, Nörskov and<br>minimile:-sturctured phosphide clearcosalisy, which<br>is eno-workers found at MoS<sub>2</sub> nanoparticles supported<br>or sity functional theory (DFT) calculations, Nörskov and<br>
inimetallic-structured phosphide electrocatalyst, which<br>
co-workers found that M6S, nanoparticles supported can thibited superior HER performance in actici, alka-<br>
o co-workers found that MoS<sub>2</sub> nanoparticles supported exhibited superior HFR performance in acidic, alka-<br>on graphic with a moderate overpotential of  $0.1 \sim$  line and neutral conditions, expanding the dimension<br>of 20.2 vis on graphite with a moderate overpotential of 0.1 ~ line and neutral conditions, expanding the dimensione-<br>C2.9 V is a promising electrocatalyst for FIR/<sup>87</sup>. Then al of both scientific and industrial fields<sup>193</sup>. On the<br>C 0.2 V is a promising electrocatalyst for HER<sup>1891</sup>. Then al of both scientific and industrial fields<sup>(13)</sup>. On the Chockcadorff and co-workers determined that the other hand, various technologies have been well emotive an Chorkendorff and co-workers determined that the other hand, various technologies have been well em-<br>edge of MoS<sub>c</sub> nanoparticles is the real active since the phosphide to reveal the catalytic mechanism of water<br>HFR via tu edge of MoS, nanoparticles is the real active sites for<br>
FIRE via tuning the state/of meconomics, function electrologis and monitor the colubrino fedectrocata-<br>
HER via tuning the size of nanoparticles, function of clothe HFR via tuning the size of nanoparticles, further electrolysis and monitor the evolution of electrocata-<br>providing an experimental foundation for optimizing by these in electrochemical operations besides<br>the intrinsic act providing an experimental foundation for optimizing lysts in electrochemical operando conditions besides<br>the intrinsic entirity decisteredly  $\frac{1}{2}$  considering decisions of<br>metal-based electrocatalysts may suffer from the intrinsic activity of electrocatalyst<sup>60</sup>. Considering designing electrocatalysts. For instance, Agnoli and metal-based electrocatalysts may suffer from corroversor selectrimed the real active sites for HER since in a

 $\# \{\nexists G \in \mathbb{R}^d : \text{L}(\text{Electrochem.}) \text{ is a 214008 (4 of 18)}\}\n\text{Donitz in 1980s, respectively (Figure 3a)^{[33]}.\n\text{And the } \text{circled a } \text{ and } \text{ adjustable coordination structure, sindevelopment of appropriate electrocatalysts with suit-} \text{gle-atom catalysts (SACs) have shown great promise able physical and chemical properties is highly re-} \text{ in water electrolysis in recent years}^{[43].\n\text{For instance, quired for water electrolysis. During the past few nitrogen-doped graphene nanosheets supported decades, numerous electrocatalysts, including noble} \text{Pt-SAC was fabricated by Sun and co-workers in the$ the velope the multiple subsective of approximation structure, sin-<br>
Donitz in 1980s, respectively (Figure 3a)<sup>[33]</sup>. And the ciency and adjustable coordination structure, sin-<br>
development of appropriate electrocatalysts  $\text{E} \&L^{\#}(J. Electron)$  2022, 28(10), 2214008 (4 of 18)<br>Donitz in 1980s, respectively (Figure 3a)<sup>[33]</sup>. And the ciency and adjustable coordination structure, sin-<br>development of appropriate electrocatalysts with suit-<br>gle-ato quired for water electrolysis. During the past few  $28(10)$ ,  $2214008$  (4 of 18)<br>ciency and adjustable coordination structure, sin-<br>gle-atom catalysts (SACs) have shown great promise<br>in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>nitrogen-doped graphene nanosh  $28(10)$ ,  $2214008$  (4 of 18)<br>ciency and adjustable coordination structure, sin-<br>gle-atom catalysts (SACs) have shown great promise<br>in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>nitrogen-doped graphene nanosh  $28(10)$ ,  $2214008$  (4 of 18)<br>ciency and adjustable coordination structure, sin-<br>gle-atom catalysts (SACs) have shown great promise<br>in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>nitrogen-doped graphene nanosh 28(10), 2214008 (4 of 18)<br>
ciency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
nitrogen-doped graphene nanosh 28(10), 2214008 (4 of 18)<br>
ciency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
nitrogen-doped graphene nanosh 28(10), 2214008 (4 of 18)<br>
ciency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
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nitrogen-doped graphene nanosh 28(10), 2214008 (4 of 18)<br>
eiency and adjustable coordination structure, sin-<br>
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eiency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup></sup> (10), 2214008 (4 of 18)<br>
mey and adjustable coordination structure, sin-<br>
atom catalysts (SACs) have shown great promise<br>
water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
rogen-doped graphene nanosheets supported<br> 28(10), 2214008 (4 of 18)<br>
ciency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>{43}</sup>. For instance,<br>
nitrogen-doped graphene nanosh 28(10), 2214008 (4 of 18)<br>
ciency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>{(8)</sup>. For instance,<br>
nitrogen-doped graphene nanosh 电化学(*J. Electrochem.*) 2022, 28(10), 2214008 (4 of 18)<br>Figure 3a)<sup>[33]</sup>. And the ciency and adjustable coordination structure, sin-<br>ctrocatalysts with suit- gle-atom catalysts (SACs) have shown great promise<br>operties is

28(10), 2214008 (4 of 18)<br>
eiency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
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eiency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
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ciency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
nitrogen-doped graphene nanosh 28(10), 2214008 (4 of 18)<br>
eiency and adjustable coordination structure, sin-<br>
gle-atom catalysts (SACs) have shown great promise<br>
in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>
nitrogen-doped graphene nanosh **Exercisy** and adjustable coordination structure, sin-<br>gle-atom catalysts (SACs) have shown great promise<br>in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>nitrogen-doped graphene nanosheets supported<br>Pt-SAC was ciency and adjustable coordination structure, sin-<br>gle-atom catalysts (SACs) have shown great promise<br>in water electrolysis in recent years<sup>[43]</sup>. For instance,<br>nitrogen-doped graphene nanosheets supported<br>Pt-SAC was fabr gle-atom catalysts (SACs) have shown great promise<br>in water electrolysis in recent years<sup>[43</sup>]. For instance,<br>mitrogen-doped graphene nanosheets supported<br>Pt-SAC was fabricated by Sun and co-workers in<br>2016 by atomic laye in water electrolysis in recent years<sup>[43</sup>]. For instance,<br>nitrogen-doped graphene nanosheets supported<br>Pt-SAC was fabricated by Sun and co-workers in<br>2016 by atomic layer deposition, which exhibited<br>much high activity an nitrogen-doped graphene nanosheets supported<br>Pt-SAC was fabricated by Sun and co-workers in<br>2016 by atomic layer deposition, which exhibited<br>much high activity and stability for HER than com-<br>mercial Pt/C<sup>144</sup>.<br>Along with Pt-SAC was fabricated by Sun and co-workers in 2016 by atomic layer deposition, which exhibited much high activity and stability for HER than commercial Pt/C<sup>144</sup>. Along with the deepening of water electrolysis, numerous 2016 by atomic layer deposition, which exhibited<br>much high activity and stability for HER than com-<br>mercial Pt/C<sup>(44)</sup>.<br>Along with the deepening of water electrolysis,<br>numerous electrocatalysts have shown promising ac-<br>ti much high activity and stability for HER than com-<br>mercial Pt/C<sup>(44)</sup>.<br>Along with the deepening of water electrolysis,<br>numerous electrocatalysts have shown promising ac-<br>tivity and stability for HER. For example,  $\gamma$ -MnO mercial Pt/C<sup>144</sup>.<br>
Along with the deepening of water electrolysis,<br>
numerous electrocatalysts have shown promising ac-<br>
tivity and stability for HER. For example,  $\gamma$ -MnO<sub>2</sub><br>
electrocatalyst developed by Nakamura and co Along with the deepening of water electrolysis,<br>numerous electrocatalysts have shown promising ac-<br>tivity and stability for HER. For example,  $\gamma$ -MnO<sub>2</sub><br>electrocatalyst developed by Nakamura and co-work-<br>ers could operat numerous electrocatalysts have shown promising ac-<br>tivity and stability for HER. For example,  $\gamma$ -MnO<sub>2</sub><br>electrocatalyst developed by Nakamura and co-work-<br>ers could operate continuously for more than 8000<br>hours<sup>1451</sup> and tivity and stability for HER. For example,  $\gamma$ -MnO<sub>2</sub><br>electrocatalyst developed by Nakamura and co-work-<br>ers could operate continuously for more than 8000<br>hours<sup>[45]</sup> and Pt/Ni-Mo electrocatalyst developed by<br>Liu and co-w electrocatalyst developed by Nakamura and co-work-<br>ers could operate continuously for more than 8000<br>hours<sup>[45]</sup> and Pt/Ni-Mo electrocatalyst developed by<br>Liu and co-workers realized an ultrahigh current den-<br>sity of 2000 ers could operate continuously for more than 8000<br>hours<sup>[45]</sup> and Pt/Ni-Mo electrocatalyst developed by<br>Liu and co-workers realized an ultrahigh current den-<br>sity of 2000 mA·cm<sup>2</sup> at an overpotential of 113 mV<sup>146</sup>,<br>demon hours<sup>[45]</sup> and Pt/Ni-Mo electrocatalyst developed by<br>Liu and co-workers realized an ultrahigh current den-<br>sity of 2000 mA · cm<sup>-2</sup> at an overpotential of 113 mV<sup>146</sup>,<br>demonstrating the feasibility for practical water el Liu and co-workers realized an ultrahigh current density of 2000 mA  $\cdot$  cm<sup>-2</sup> at an overpotential of 113 mV<sup>tes</sup>,<br>demonstrating the feasibility for practical water electrolysis. Meanwhile, Hu and co-workers prepared a<br>b catalysis<sup>[47]</sup>. monstrating the feasibility for practical water elec-<br>Mysis. Meanwhile, Hu and co-workers prepared a<br>metallic-structured phosphide electrocatalyst, which<br>hibited superior HER performance in acidic, alka-<br>e and neutral cond trolysis. Meanwhile, Hu and co-workers prepared a<br>bimetallic-structured phosphide electrocatalyst, which<br>exhibited superior HER performance in acidic, alka-<br>line and neutral conditions, expanding the dimension-<br>al of both bimetallic-structured phosphide electrocatalyst, which<br>exhibited superior HER performance in acidic, alka-<br>line and neutral conditions, expanding the dimension-<br>al of both scientific and industrial fields<sup>[15]</sup>. On the<br>oth exhibited superior HER performance in acidic, alka-<br>line and neutral conditions, expanding the dimension-<br>al of both scientific and industrial fields<sup>[15]</sup>. On the<br>other hand, various technologies have been well em-<br>ployed line and neutral conditions, expanding the dimension-<br>al of both scientific and industrial fields<sup>[15]</sup>. On the<br>other hand, various technologies have been well em-<br>ployed to reveal the catalytic mechanism of water<br>electro al of both scientific and industrial fields<sup>[15]</sup>. On the<br>other hand, various technologies have been well em-<br>ployed to reveal the catalytic mechanism of water<br>electrolysis and monitor the evolution of electrocata-<br>lysts

other hand, various technologies have been well em-<br>ployed to reveal the catalytic mechanism of water<br>electrolysis and monitor the evolution of electrocata-<br>lysts in electrochemical operando conditions besides<br>designing e ployed to reveal the catalytic mechanism of water<br>electrolysis and monitor the evolution of electrocata-<br>lysts in electrochemical operando conditions besides<br>designing electrocchemical operando conditions besides<br>designin electrolysis and monitor the evolution of electrocata-<br>lysts in electrochemical operando conditions besides<br>designing electrocatalysts. For instance, Agnoli and<br>co-workers determined the real active sites for HER<br>via the lysts in electrochemical operando conditions besides<br>designing electroccatalysts. For instance, Agnoli and<br>co-workers determined the real active sites for HER<br>via the electrochemical scanning tunnelling mi-<br>croscopy, provi designing electrocatalysts. For instance, Agnoli and<br>co-workers determined the real active sites for HER<br>via the electrochemical scanning tunnelling mi-<br>croscopy, providing a powerful tool to derive accu-<br>rate structure-a  $\frac{d}{dt}\mathcal{H}^{\#}(J. Electron) \cdot 2022, 28(10), 2214008 (5 of 18)$ <br>
Hydrothermal method, which shows remarkable activalloys, oxides, carbides, sulfides, nitrides, selenides<br>
ity and durability for AWE (Figure 3b)<sup>[83]</sup>. The over-<br>
and outperforming most reported electrocatalysts. More- $\frac{\pm (E\# (J. Electrochem.) 2022, 28(10), 2214008 (5 of 18))}{\pm 0.2244008 (5 of 18)}$ <br>
by determined which shows remarkable activerially some synthesized with LDHs as pre-<br>
potentials at the current density of 10 mA · cm<sup>2</sup> for cor-<br>
potenti **EVALUATION THE EXAMON CONTROLLAT THE SET ALLOWS CONTROLLAT THE SET ASSEMBLY THE COP CONTROLLAT THE SET ASSEMULT AS THE SET ARRENT THE SUPPOSE THE RAD OF R WE THE SUPPOSE THE RAD OF R were 130 and 270 mV, respectively, wh**  $\pm$  *Reetrochem.*) 2022, 28(10), 2214008 (5 of 18)<br>hydrothermal method, which shows remarkable activ-<br>ity and durability for AWE (Figure 3b)<sup>(33)</sup>. The over-<br>and phosphides were synthesized with LDHs as pre-<br>potentials a **in which FeCoP exhibited significantly enhanced ac-**<br> **interpretentation** external method, which shows remarkable activeringly, oxides, carbides, sulfides, nitrides, selenides<br>
ity and durability for AWE (Figure 3b<sup>1581</sup> the mass of content and the more than the subsect of the subsect of the subsection of subsection of electrochemic strength of the americ and phosphides were synthesized with LDHs as prepotentials at the current density of  $\pm$  (E $\pm$  Rectrocknean, 2022, 28(10), 2214008 (5 of 18)<br>
hydrothermal method, which shows remarkable activerables, scories, carbides, sulfides, nitrides, selenides<br>
ity and durability for AWE (Figure 3b<sup>1/30</sup>. The overthe entertainment density of Electrocal method, which shows remarkable active<br>
thydrothermal method, which shows remarkable active<br>
in allows, oxides, carbides, sulfrides, nitrides, selenides<br>
ity and durability for AWE **then**<br>  $\Phi/E^2(LElectrochem, 2022, 28(10), 2214008 (5 of 18)$ <br>
hydrothermal method, which shows remarkable activeary alloys, oxides, earbides, sulfides, nitrides, selenides<br>
ity and durability for AWE (Figure 3b)<sup>[81]</sup>. The over-<br>
ac  $\text{#}(R \# \langle L \text{~Electrochem.}) 2022, 28(10), 2214008 (5 of 18)$ hydrothermal method, which shows remarkable active<br>
ity and durability for AWE (Figure 3b)<sup>503</sup>. The over-<br>
and phosphides were synthesized with LDHs as pre-<br>
potentials the  $2^k(L$  *Electrodeum*.) 2022, 28(10), 2214008 (5 of 18)<br>thydrothermal method, which shows remarkable active alloys, oxides, carbides, sulfides, nitrides, selenides<br>ity and durability for AWE (Figure 3b)<sup>(31)</sup>. The over and restrict in the term of the theorem and the term of the structure ratios of the structure ratios is a physical central and the current density and durability for AWE (Figure 3p)<sup>281</sup>. The over-<br>and phosphides were syn hydrothermal method, which shows remarkable activ-<br>alloys, oxides, sulfides, sulfides, rainics; selenides<br>ity and durability for AWF. (Figure 3)<sup>1991</sup>. The over-<br>orientalis at the current density of 10 mA - cm<sup>-2</sup> for cur

 $# \ell \neq (J. \text{Electrochem.}) 2022, 28(10), 2214008 (5 of 18)$ <br>hydrothermal method, which shows remarkable activ-<br>illoys, oxides, carbides, sulfides, nitrides, selenides<br>ity and durability for AWE (Figure 3b)<sup>[53]</sup>. The over-<br>potentials ity and durability for AWE (Figure 3b)[53]. The over- $# \&L^{\#}(L \&Electrochem.) 2022, 28(10), 2214008 (5 of 18)$ <br>
hydrothermal method, which shows remarkable activ-<br>
alloys, oxides, carbides, sulfides, nitrides, selenides<br>
ity and durability for AWE (Figure 3b)<sup>[53]</sup>. The over-<br>
and ph 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to  $28(10)$ ,  $2214008$  (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective rout 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to cations<sup>[51]</sup>. 10), 2214008 (5 of 18)<br>
bys, oxides, carbides, sulfides, nitrides, selenides<br>
14 phosphides were synthesized with LDHs as pre-<br>
sors through topological transformation strategy,<br>
ich opens up an effective route to rationa 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 电化学(*J. Electrochem.*) 2022, 28(10), 2214008 (5 of 18)<br>
nows remarkable activ-<br>
alloys, oxides, carbides, sulfides, nitrides, selenides<br>
gure 3b)<sup>[53]</sup>. The over-<br>
and phosphides were synthesized with LDHs as pre-<br>
ty of

28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to 28(10), 2214008 (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to  $28(10)$ ,  $2214008$  (5 of 18)<br>alloys, oxides, carbides, sulfides, nitrides, selenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective rout  $\frac{\text{gcd}(x_0, 221,000 \text{ C} \text{C} \text{F} \text{F} \text{O}}{100 \text{ s}}$  and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to rational design<br>and fabri alloys, oxides, carbides, sulfides, nitrides, elenides<br>and phosphides were synthesized with LDHs as pre-<br>cursors through topological transformation strategy,<br>which opens up an effective route to rational design<br>and fabric



[53]

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	Table 1 Summary of AWE performance from recently reported work			
Electrocatalyst	Overpotential/V	Stability/h	Ref.	
C: CoNiP@LDH A: CoNiP@LDH	$1.44@10 \text{ mA} \cdot \text{cm}^2$	$20@10 \text{ mA} \cdot \text{cm}^2$	$[59]$	
$C: (Ni, Fe)S_2@MoS_2$ A: (Ni,Fe)S <sub>2</sub> @MoS <sub>2</sub>	$1.56@10 \text{ mA} \cdot \text{cm}^{-2}$	$24@10$ mA $\cdot$ cm <sup>-2</sup>	$[53]$	
C: Ni-MoN A: stainless-steel mat	$1.613@100 \text{ mA} \cdot \text{cm}^{-2}$	$100@100$ mA $\cdot$ cm <sup>-2</sup>	$[28]$	
$C: Ni(OH)2/Ni3S2$ A: $Ni(OH)2/Ni3S2$	$1.49@10 \text{ mA} \cdot \text{cm}^{-2}$	$120@20 \text{ mA} \cdot \text{cm}^{-2}$	$[24]$	
C: NF-Na-Fe-Pt A: NF-Na-Fe-Pt	$1.56@10 \text{ mA} \cdot \text{cm}^{-2}$	$12@10 \text{ mA} \cdot \text{cm}^2$	$[62]$	
C: FeCoP A: FeCoP	$1.60@10 \text{ mA} \cdot \text{cm}^{-2}$	$20(a)10$ mA $\cdot$ cm <sup>-2</sup>	$[54]$	
C: FeCoNi(S) A: FeCoNi(S)	$1.53@10 \text{ mA} \cdot \text{cm}^{-2}$	$2000(a)500 \text{ mA} \cdot \text{cm}^{-2}$	$[64]$	
C: Ni-Co-Fe-P A: Ni-Co-Fe-P	$1.46@10 \text{ mA} \cdot \text{cm}^{-2}$	$100\omega$ <sub>2</sub> 100 mA $\cdot$ cm <sup>-2</sup>	[60]	
C: Ni <sup>m</sup> Co <sup>n</sup> Fe-O@NF A: Ni <sup>m</sup> Co <sup>n</sup> Fe-O@NF	$1.455@10 \text{ mA} \cdot \text{cm}^{-2}$	$100@1.53$ V	[61]	
C: CoFeP TPAs A: CoFeP TPAs	$1.47@10 \text{ mA} \cdot \text{cm}^{-2}$	$100@20$ mA $\cdot$ cm <sup>-2</sup>	$[63]$	

A: FeCoN(8)<br>
C:N:Co-Fe-P<br>
C:N:Co-Fe-P<br>
A:N:Co-Fe-P<br>
A:N:Co-Fe-P<br>
A:N:Co-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O-Fe-P<br>
C:N:Te-O C. Ni-Co-Fe-P<br>
A.Ni-Co-Fe-P<br>
A.Ni-Co-Fe-P<br>
A.Ni-Co-Fe-P<br>
A.Ni-Co-Fe-P<br>
C. Ni-PCo-Fe-O@NF<br>
1.455@10 mA·cm<sup>2</sup><br>
1.40@210 mA·cm<sup>2</sup><br>
1.60@15.53 V<br>
161]<br>
C. Co-fe-P TPA<sub>A</sub><br>
A.Co-Fe-P TPA<sub>A</sub><br>
A.Co-Fe-P TPA<sub>A</sub><br>
A.Co-Fe-P TPA<sub>A</sub><br> As NiCo-FeP<br>
C-NiCo-FeO MAT and S6 and the most of the consideration<br>  $\Delta t$  NiCo-FeO MAT and  $\Delta t$  are considered as Pranch and S6 and S6 multiplation (and S6 and S6 multiplation of C:NTCCTe-OG@NT<br>
A:NTCOFe-OG@NT<br>
A:CoFeP TPAs<br>  $A: CoFeP$  TPAs<br>  $A: CoFeP$ Symmetric materials at the contest process of AWE (for the the contest on the contest of the current on AC ( $\alpha$ -Ceo PT) at an anotomic mode and a cathodo, the ohmic resistention of electrocatalysts have wincessed conside demonstraing an excellent durability. Although non-<br>
sustained and a cathode, the ohmic resis-<br>
moble metal electrocatalysts have winessed consider-<br>
tance caused by clectron transfer of electrode, ions<br>
alse progress, no demonstrating an excellent durability. Although non-<br>
process at an anode and<br>
noble metal electrocatalysts have witnessed consider-<br>
ance caused by electron<br>
ance Pr and Ru) still play an irreplaceable role in water<br>
ele demonstrating an excellent durability. Although non-<br>
process at an anode and a cathode, the ohmic resis-<br>
moleh metal electrocallysts have witnessed consider-<br>
ance caused by electron transfer of electrode, ions<br>
alle pro ble metal electrocatalysts have winnessed consider-<br>
trance caused by electron transfer of electrode, ions<br>
derivated electrocatalysts (such that diffusion of electroty and membrane, and generated<br>
the ad Ru) still play a able progress, noble metal-based electrocetallysts (such<br>
airflusion of electrolyte and membrane, and generated<br>
as Pr and Ru) still play an irreplaceable one in water<br>
electrolysis. Numerous studies have shown that Pt is<br> as Pt and Ru) still play an irreplaceable role in water<br>
electrologies. Numerous surfaise have shown that Pt is Through rational designing the applied potential.<br>
ethe chromation surfaise have shown that Pt is Through rati electrolysis. Numerous studies have shown that Pt is<br>
the benchmarking HER electrocatalyst, while its over-<br>
electrocatalyst, but is operator on to hy am improve the mass-loading of<br>
full water splitting performance is st

 $n^2$   $12@10 \text{ mA} \cdot \text{cm}^2$   $[62]$ <br>  $n^3$   $20@10 \text{ mA} \cdot \text{cm}^2$   $[54]$ <br>  $n^2$   $200@500 \text{ mA} \cdot \text{cm}^2$   $[64]$ <br>  $n^2$   $100@100 \text{ mA} \cdot \text{cm}^2$   $[60]$ <br>  $n^2$   $100@20 \text{ mA} \cdot \text{cm}^2$   $[63]$ <br>  $n^2$   $100@20 \text{ mA} \cdot \text{cm}^2$   $[63]$ <br>  $n^2$  20@10 mA · cm<sup>2</sup> [54]<br>  $n^2$  2000@500 mA · cm<sup>2</sup> [64]<br>  $n^3$  100@100 mA · cm<sup>2</sup> [60]<br>  $n^2$  100@20 mA · cm<sup>2</sup> [63]<br>  $n^2$  100@20 mA · cm<sup>2</sup> [63]<br> **process at an anode and a cathode, the ohmic resis-<br>
tance caused by**  $20@10 \text{ mA} \cdot \text{cm}^2$  [54]<br>  $m^2$   $2000@500 \text{ mA} \cdot \text{cm}^2$  [64]<br>  $m^2$   $100@100 \text{ mA} \cdot \text{cm}^2$  [60]<br>  $m^2$   $100@20 \text{ mA} \cdot \text{cm}^2$  [63]<br>  $m^2$   $100@20 \text{ mA} \cdot \text{cm}^2$  [63]<br> **process at an anode and a cathode, the ohmic resi**  $n^2$  2000@500 mA·cm<sup>2</sup> [64]<br>  $n^2$  100@100 mA·cm<sup>2</sup> [60]<br>  $n^2$  100@153 V [61]<br>  $n^3$  100@220 mA·cm<sup>2</sup> [63]<br> **Process at an anode and a cathode, the ohmic resis-<br>
tance caused by electron transfer of electrode, ions<br>
dif**  $2000\,\text{g}200\,\text{mA}\cdot\text{cm}^2$  [64]<br>  $\text{m}^2$  100@100 mA  $\cdot\text{cm}^2$  [60]<br>  $\text{m}^2$  100@22 mA  $\cdot\text{cm}^2$  [63]<br>  $\text{process at an anode and a cathode, the ohmic resis-}$ <br>
process at an anode and a cathode, the ohmic resis-<br>
tance caused by electron transf 100@100 mA  $\cdot$  cm<sup>2</sup> [60]<br>
<sup>2</sup> 100@1.53 V [61]<br>
100@20 mA  $\cdot$  cm<sup>2</sup> [63]<br> **100** cm20 mA  $\cdot$  cm  $m^2$  100@1.53 V [61]<br>  $m^2$  100@20 mA · cm<sup>2</sup> [63]<br> **process at an anode and a cathode, the ohmic resis-<br>
tance caused by electron transfer of electrode, ions<br>
diffusion of electrolyte and membrane, and generated<br>
gas bu** the more increases are more effectively, and excellent stability, and as permeability, and as permetionic and the more effective and membrane, and generated gas bubbles, further increasing the applied potential.<br>Through r  $n^2$  100@20 mA·cm<sup>2</sup> [63]<br>
Process at an anode and a cathode, the ohmic resistance caused by electron transfer of electrode, ions diffusion of electrolyte and membrane, and generated gas bubbles, further increasing the a  $n^2$  100@20 mA cm<sup>2</sup> [63]<br>
process at an anode and a cathode, the ohmic resistance caused by electron transfer of electrode, ions diffusion of electrolyte and membrane, and generated gas bubbles, further increasing the a

process at an anode and a cathode, the ohmic resis-<br>tance caused by electron transfer of electrode, ions<br>diffusion of electrolyte and membrane, and generated<br>gas bubbles, further increasing the applied potential.<br>Through r process at an anode and a cathode, the ohmic resis-<br>tance caused by electron transfer of electrode, ions<br>diffusion of electrolyte and membrane, and generated<br>gas bubbles, further increasing the applied potential.<br>Through r process at an anode and a cathode, the ohmic resis-<br>tance caused by electron transfer of electrode, ions<br>diffusion of electrolyte and membrane, and generated<br>gas bubbles, further increasing the applied potential.<br>Through r tance caused by electron transfer of electrode, ions<br>diffusion of electrolyte and membrane, and generated<br>gas bubbles, further increasing the applied potential.<br>Through rational designing the structure of current<br>collector diffusion of electrolyte and membrane, and generated<br>gas bubbles, further increasing the applied potential.<br>Through rational designing the structure of current<br>collector not only can improve the mass-loading of<br>electrocata gas bubbles, further increasing the applied potential.<br>Through rational designing the structure of current collector not only can improve the mass-loading of electrocatalyst, but also promote the desorption and diffusion o Through rational designing the structure of current<br>collector not only can improve the mass-loading of<br>electrocatalyst, but also promote the desorption and<br>diffusion of generated gas, which is conducive to the<br>progress of  $\frac{16}{2}$  (*LEectrochem.*) 2022, 28(10), 2214008 (7 of 18)<br>
using of binder can bring about severe aggregation of bubbles during AWE process can also be desorbed<br>
electrocatalyst and limited diffusion of electrolyte, ins ation will lead to the decomposition of binder and dethe electrocatalyst and iming about severe aggregation of bubbles during AWE process can also be desorbed<br>electrocatalyst and limited diffusion of electrolyte, instantaneously ewing to the ordered stucture (Fig-<br>and thus which seriously limits its practical application. ts  $\ell E^{\infty}(L$  *Electrochem*.) 2022, 28(10), 2214008 (7 of 18)<br>using of binder can bring about severe aggregation of bubbles during AWE process can also be desorbed<br>electrocatalyst and limited diffusion of electrolyte, in  $\frac{\text{tfk2}^{\infty}(L\text{~Reemochem.})\cdot 2022, 28(10), 2214008 (7 of 18)}{\text{using of bindder can bring about severe aggregation of\n \n- bubble, maximumsC14008 (7 of 18)
\n
\n\n- disag of binder can bring about severe aggregation of\n
	\n- subbles
	\n- instantaneously owing to the ordered structure (Figa- and other) and following
	\n\n
\n- the harsh electrolyte environment or continuous oper-  
\n
	\n- participate next cataltyic process<sup>[38]</sup>. Moreover, the in-  
	\n also the decomposition of binder and de$ 

 $\#E\#(J. \text{Electrochem.})$  2022, 28(10), 2214008 (7 of 18)<br>using of binder can bring about severe aggregation of bubbles during AWE process can also be desorbed<br>electrocatalyst and limited diffusion of electrolyte, instantaneousl  $\#E\#$  (*J. Electrochem.*) 2022, 28(10), 2214008 (7 of 18)<br>using of binder can bring about severe aggregation of bubbles during AWE process can also be desorbed<br>electrocatalyst and limited diffusion of electrolyte, insta  $\exists \{E \neq (L \: \textit{Electrochem.})\ 2022, 28(10), 2214008 \: (\text{7 of 18})\}$ using of binder can bring about severe aggregation of bubbles during AWE process can also be desorbed electrocatalyst and limited diffusion of electrolyte, instant  $\pm \frac{R}{2}(L\text{ Electrowe}, \ln 222, 28(10), 2214008 (7 of 18))$ <br>and the margin about severe aggregation of bubbles during AWE process can also be desorbed<br>trocatalyst and limited diffusion of electrolyte, instantaneously owing to the or  $28(10)$ ,  $2214008$  (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[7</sup>  $28(10)$ ,  $2214008$  (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[7</sup> 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. 10), 2214008 (7 of 18)<br>
bbles during AWE process can also be desorbed<br>
tantaneously owing to the ordered structure (Fig-<br>
24d), thus letting the active site be exposed and<br>
ticipate next catalytic process<sup>[72]</sup>. Moreover,  $28(10)$ ,  $2214008(7 \text{ of } 18)$ <br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Figure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[73</sup> 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>173</sup>. 电化学(*J. Electrochem.*) 2022, 28(10), 2214008 (7 of 18)<br>
t severe aggregation of bubbles during AWE process can also be desorbed<br>
ffusion of electrolyte, instantaneously owing to the ordered structure (Fig-<br>
formance. In

**EVALUATION EXAMON (Follow A step of the set of the set** trodes with various nanostructures (e.g., nanorod, **EVALUATION THE UNITE (SCUPEC ALL ANTER CONDUPLE THE UNITE USE A CONDUPLE THE UNITE (SCUPET A THE ART AND A CONDUPLE THE UNITE (SCUPET A THE ART AND A CONDUPLE THE UNITE (SCUPET A THE ART AND HERE INTO A THE UNITE (SCUPET**  $\frac{\#_1(E \oplus L(E) \cdot E) \cdot E) \cdot E \cdot E} {\#_1(E \oplus L(E) \cap E) \cdot E} \cdot \frac{\#_1(E \oplus L(E) \cap E) \cdot E} {\#_1(E) \cap E} \cdot \frac{\#_1(E \oplus L(E) \cap E) \cdot E} {\#_1(E) \cap E} \cdot \frac{\#_1(E) \cap E} {\#_1(E) \cap E} \cdot \frac{\#_1(E) \$ and hydrothermal methods (Figure 4c)[59, 67-70]. The inusing of binder can bring about severe agregation of bubbles during AWE process can also be desorbed<br>electrocatalyst and limited diffusion of electrolyte, instantaneously owing to the ordered structure (Fig-<br>and thus resu using of binder can bring about severe aggregation of<br>
electrocatalyst and timited diffusion of electrotye, instantaneously owing to the ordered structure (Fig-<br>
electrocatalyst and timited diffusion of electrolyte, insta electrocatalyst and limited diffusion of electrolyte, instantaneously owing to the ordered structure (Fig-<br>and thus result in inferior performance. In addition, ure 4d), thus letting the active site be exposed and<br>the har and thus result in inferior performance. In addition, ure 4d), thus letting the active site be exposed and<br>the harsh electrolyte environment or continuous oper-<br>participate next catalytic process<sup>pac</sup>. Moreover, the in-<br>t 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>173</sup>.  $28(10)$ ,  $2214008$  (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[7</sup> 28(10), 2214008 (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>.  $28(10)$ ,  $2214008$  (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[7</sup>  $28(10)$ ,  $2214008$  (7 of 18)<br>bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[7</sup> **Example 12**<br> **Subtismum AWE** process can also be desorbed<br>
instantaneously owing to the ordered structure (Fig-<br>
ure 4d), thus letting the active site be exposed and<br>
participate next catalytic process<sup>[72]</sup>. Moreover, t bubbles during AWE process can also be desorbed<br>instantaneously owing to the ordered structure (Fig-<br>ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. Moreover, the in-<br>tegrated instantaneously owing to the ordered structure (Figure 4d), thus letting the active site be exposed and participate next catalytic process<sup>[72]</sup>. Moreover, the integrated structure can also strengthen the connection betwe ure 4d), thus letting the active site be exposed and<br>participate next catalytic process<sup>[72]</sup>. Moreover, the in-<br>tegrated structure can also strengthen the connection<br>between electrocatalyst and collector, and improve<br>the



 $\text{t}E\#(J. Electron)$ <br>generated from the electrolyte between two elec-<br>trodes is decreased since the distance between two elec-<br>trodes is decreased since the distance between two introduces abundant oxygen vacancies on the CoAl  $\text{tR} \text{#}(J. \text{Electrochem.})$  2022, 28(10), 2214008 (8 of 18)<br>generated from the electrolyte between two elec-<br>trodes is decreased since the distance between two introduces abundant oxygen vacancies on the CoAl-<br>electrodes is a

in which the anodic OER can be replaced with other<br>easy oxidation reactions, such as organic (e.g., alco-<br>easy oxidation reactions, such as organic (e.g., alco-<br>hols, aldehydes and amines) oxidation reaction<sup>179</sup>. highly-

 $# \ell \neq (L \ \text{Electrochem.}) 2022, 28(10), 2214008 (8 of 18)$ generated from the electrolyte between two electron (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
trodes is decreased since the distance between two introduces abu **To further accelerate** the removal of the gas products abundant oxygen vacancies on the CoAlectrodes is almost the same thickness during AWE, the gas diffusion layer is integrated with the  $R^2$ (*J. Electrochem.*) 2022, 28(10), 2214008 (8 of 18)<br>generated from the electrolyte between two elec-<br>tion (Figure 5b)<sup>157</sup>. The *in-situ* exfoliation<br>trodes is decreased since the distance between two introduces  $\pm \frac{2.3}{2}$  Coupling with Organic Oxidation process is well as much in the referable energy expected from the electrodyte between two electrom (Figure 5b)<sup>[37]</sup>. The *in-situ* exfoliation strategy trotes is decreased si  $\pm$ (EF  $Electrochem$ ) 2022, 28(10), 2214008 (8 of 18)<br>
nerated from the electrolyte between two elec-<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfolution strategy<br>
des is decreased since the distance between two elec-<br>
tiroduces **E** *(Electrochem.*) 2022, 28(10), 2214008 (8 of 18)<br>
generated from the electrolyte between two electron (Figure 5b)<sup>591</sup>. The *in-situ* exfoliation strategy<br>
trodes is decreased since the distance between two electron i **EVALUATION 1908**<br> **EXALUATION 1908** (8 of 18)<br> **Examplemented** from the electrolyte between two electron (Figure 5b)<sup>157</sup>. The *in-situ* exfoliation strategy<br>
trodes is decreased since the distance between two introduces seriously restricts the hydrogen production efficiency **Example 12**<br> **Example 12**  $\frac{\ln\{\mu^{\omega}(t, L \text{letermeden})\ 2022, 28(10), 2214008 (8 of 18)}{\text{corrected}}\n\text{for the electrowe} \text{ to the discrete tree} \quad \text{for (Figure 5b)}^{[181]} \text{ The } in-situ \text{ exclusion strategy} \text{ trotes is almost the same thickness of membrane. } \text{LDH}, \text{ which regulates the electron is structure of the first time, and the difference between two introduces subundant oxygen vacancies on the CoAl-heletodes is almost the same thickness of membrane. } \text{LDH}, \text{ which regulates the adsorption and oxidation during AWF, the gas diffusion layer is integrated with the model of the gas products. } \text{LDH}, \text{ and facilitates the adsorption$ **EXALLE 1999**<br> **Example 10** The electroids in the electronic state of the distance between two electronic state accords is decreased since the distance between two introduces abundant roxygen vacancies on the CoAlectrodes the  $2\pi (f. Riem)$  and the electrolyte between two elec-<br>tion (Figure 5b)<sup>173</sup>. The *in-situ* exfoliation strategy<br>trodes is decreased since the distance between two elec-<br>tion (Figure 5b)<sup>173</sup>. The *in-situ* exfoliation str generated from the electrolyte between two elec-<br>
ion (Figure 5b)<sup>173</sup>. The *in-situ* exfoliation strategy<br>
trodes is decreased since the distance between two<br>
introduces abundant oxygen vacancies on the CoAl-<br>
electrodes generated from the electrolyte between two elec-<br>
trols is decreased since the distance between two introduces abundant oxygen variancies on the CoAl-<br>
relectrodes is almost the same thickness of membrane. LDH, which regu trodes is decreased since the distance between two introduces abundant oxygen vacancies on the CoAl-<br>electrodes is almost us smallent ance formerlane. LDH, which regulates the electronic structure of<br>To further accelerate electrodes is almost the same thickness of membrane. LDH, which regulates the electronic structure of<br>To furthe accelerate the removal of the gas products<br>
LDHs, and facilitates the ealergation and oxidation<br>
during AWE, To further accelerate the removal of the gas products<br>
aduration species of HMF, to gas advitain and oxidation<br>
during AWE, the gas diffusion layer is integrated with process of HMF. As a result, the E-CoAl-LDH-NSA<br>
the b during AWF, the gas diffusion layer is integrated with<br>
choopse plate (Eigenve 4g).<br> **2.3** Coupling with Organic Oxidation<br>
2.3 Coupling with Organic Oxidation<br>
2.3 Coupling with Organic Oxidation<br>
2.7 Coupling with Organ the bipolar plate (Figure 4g).<br> **Calcupling with Organic Oxidation** of HMF to 2,5-diramidearboxylis aid (FDCA) with a<br> **CALCUPE (FIGUS** CONFIRMET CONDITION (FOR THE TO THE TOOL) with a<br>
undergo a complex four-electron rea **2.3 Coupling with Organic Oxidation** of HMF to 2,5-furandicarboxylic scid (FDCA) with a<br>During AWE process, the anoito CBR needs to low potential of 1.30 V vs. RHE at 10 mA cm<sup>3</sup> as<br>undergo a complex four-clearon reactio During AWF process, the anodic OFR needs to<br>
low potential of 1.30 V vs. RHE at 10 mA - cm<sup>2</sup> as<br>
undergo a complex four-electron reaction process well as much high Faradice efficiency (*FE*) for FDC-<br>
and consumes more t undergo a complex four-electron reaction process<br>
well as much high Faradaic efficiency (FF) for FDCA<br>
and consumes more than 90% input energy, which  $(99.4\%)$  even at 1.52 V vs. RHE, which are the high-<br>
series the hydro and consumes more than 90% input energy, which (99.4%) even at 1.52 V vs. RHF, which are the high-<br>scriously restricts the hydrogen production efficiency est level compared with the reported electrocatalysts<br>of the cathod estiously restricts the hydrogen production efficiency<br>of the value-addot the reported electrocatalysts.<br>
of the cahood. In additional gas separation HMF exidadion coupled hydrogen generation system<br>
operator GOER (Og) ne of the cathode. In addition, the low value-added Based on the F-CoAl-LDH-NSA, we constructed<br>product of OER (O) necess additional gas separation  $\mu$  HMF oxidation coupled hydrogen generation system<br>retegs further increas product of OER (O<sub>2</sub>) needs additional gas separation  $1$  HMF oxidation coupled hydrogen generation system<br>tiens further increasing the cost of hydrogen produc-<br>for a new cleared cell, which exhibited a low voltage<br>ation. steps further increasing the cost of hydrogen produc-<br>in a two-electrode cell, which exhibited a low voltage<br>dion. Therefore, how to reduce the overpotential of of 1.74 V to reach 50 mA - en<sup>2</sup>, high H<sub>2</sub> yield of<br>anodic tion. Therefore, how to reduce the overpotential of of 1.74 V to reach 50 mA - em<sup>2</sup>, high H<sub>2</sub> yield of another eaction and achieve efficiently *in-stim* anse of  $44.16 L + h<sup>1</sup> m<sup>2</sup>$  ef 4 times higher than overall v anodic reaction and achieve efficiently *in-situ* use of  $44.16 \text{ L} \cdot \text{h}^4 \cdot \text{m}^2$  (4 times higher than overall water<br>generated oxygen is very important for the develop-<br>splitting) gas well as excellent rashing. A hi generated oxygen is very important for the develop-<br>splitting) as well as excellent stability. A hierarchical<br>ment of hydrogen production from AWF. Recently, CoNi-LDHs with abundant Ni vacancies (VNi-CoNi-<br>we proposed a c ment of hydrogen production from AWE. Recently, CoNi-LDHs with abundant Ni vacencies (VNi-CoNi-<br>we reposed a concept of electrochemical hydrogen LDH) was reported by our group, which exhibited<br>evolution coupled with altern we proposed a concept of electrochemical hydrogen<br>
covibility alternative oxidation (EHCO), superior activity for both anodic COFR and be related with other those in which the anodic COFR can be replaced with other those evolution coupled with alternative oxidation (EHCO), superior activity for both anodic HMFOR and ca-<br>in which the modic OER can be replaced with other thoic HER<sup>(19)</sup>. The EHCO based on VNi-CoNi-LDH<br>in which the correlati y oxidation reactions, such as organic (e.g., alcosare successfully realized the continuous synthesis of s, aldehydes and amines) oxidation reaction <sup>179</sup>. In large EIECO route not only reduces the anodic oxida-<br>
imply-pu hols, aldehydes and amines) oxidation reaction<sup>[28]</sup>. highly-pure FDCA and enhanced hydrogen production time EHCO route not only reduces the andio exida-<br>tion overpotential and improves the enficiency of hy-<br>bifunctional The EHCO route not only reduces the anodic oxida-<br>
tion (49.25 L·m<sup>-2</sup>·h<sup>-1</sup>). In order to further enhance the<br>
dion overpotential and improves the efficiency of hy-<br>
bimentional activity of LDH-hased electrocatalyst for<br> tion overpotential and improves the efficiency of hy-<br>
bifunctional activity of LDH-hased electrocatalyst for<br>
drog proporteion at the canhod, but also obtains the both HMPOR and HER, we prepared a bifunctional<br>
high valu drogen production at the cathode, but also obtains the<br>
both HMFOR and HER, we prepared a bifunctional<br>
high value-added chemicals and further reduces the<br>
cost of hydrogen production, which is expected to<br>
via a phosphid high value-added chemicals and further reduces the CoNiP nanosheet integrated electrode (CoNiP-NIE)<br>cost of hydrogen production, which is expected to via a phosphidation process has<br>ed on LDHS, which<br>provide a new idea fo  $28(10)$ ,  $2214008$  (8 of 18)<br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorpt  $28(10)$ ,  $2214008$  (8 of 18)<br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorpt  $28(10)$ ,  $2214008$  (8 of 18)<br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorpt 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
introduces abundant oxygen vacancies on the CoAl-<br>
LDH, which regulates the electronic structure of<br>
LDHs, and facilitates the adsorpt 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
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LDH, which regulates the electronic structure of<br>
LDHs, and facilitates the adsorpt 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
introduces abundant oxygen vacancies on the CoAl-<br>
LDH, which regulates the electronic structure of<br>
LDHs, and facilitates the adsorpt 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
introduces abundant oxygen vacancies on the CoAl-<br>
LDH, which regulates the electronic structure of<br>
LDHs, and facilitates the adsorpt  $28(10)$ ,  $2214008 (8 \text{ of } 18)$ <br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorp  $28(10)$ ,  $2214008 (8 \text{ of } 18)$ <br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorp 28(10), 2214008 (8 of 18)<br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorption 28(10), 2214008 (8 of 18)<br>tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorption 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
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LDH, which regulates the adsorpti 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
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tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
introduces abundant oxygen vacancies on the CoAl-<br>
LDH, which regulates the electronic structure of<br>
LDHs, and facilitates the alsorpt 28(10), 2214008 (8 of 18)<br>
tion (Figure 5b)<sup>157)</sup>. The *in-situ* exfoliation strategy<br>
introduces abundant oxygen vacancies on the CoAl-<br>
LDH, which regulates the electronic structure of<br>
LDH, which regulates the alsorpti **Example 18.16**<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
introduces abundant oxygen vacancies on the CoAl-<br>
LDH, which regulates the electronic structure of<br>
LDHs, and facilitates the adsorption and ox e 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>abundant oxygen vacancies on the CoAl-<br>ch regulates the electronic structure of<br>f facilitates the adsorption and oxidation<br>HMF. As a result, the E-CoAl-LDH-NSA<br>outstanding p tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorption and oxidation<br>process of H introduces abundant oxygen vacancies on the CoAl-<br>LDH, which regulates the electronic structure of<br>LDHs, and facilitates the adsorption and oxidation<br>process of HMF. As a result, the E-CoAl-LDH-NSA<br>exhibited outstanding p LDH, which regulates the electronic structure of LDHs, and facilitates the adsorption and oxidation process of HMF. As a result, the E-CoAl-LDH-NSA exhibited outstanding performance for the oxidation of HMF to 2,5-furandi LDHs, and facilitates the adsorption and oxidation<br>process of HMF. As a result, the E-CoAl-LDH-NSA<br>exhibited outstanding performance for the oxidation<br>of HMF to 2,5-furandicarboxylic acid (FDCA) with a<br>low potential of 1. process of HMF. As a result, the E-CoAl-LDH-NSA<br>exhibited outstanding performance for the oxidation<br>of HMF to 2,5-furandicarboxylic acid (FDCA) with a<br>low potential of 1.30 V vs. RHE at 10 mA  $\cdot$  cm<sup>2</sup> as<br>well as much hi exhibited outstanding performance for the oxidation<br>of HMF to 2,5-furandicarboxylic acid (FDCA) with a<br>low potential of 1.30 V vs. RHE at 10 mA  $\cdot$  cm<sup>2</sup> as<br>well as much high Faradaic efficiency (FE) for FDCA<br>(99.4%) eve of HMF to 2,5-furandicarboxylic acid (FDCA) with a<br>low potential of 1.30 V vs. RHE at 10 mA  $\cdot$  cm<sup>2</sup> as<br>well as much high Faradaic efficiency (FE) for FDCA<br>(99.4%) even at 1.52 V vs. RHE, which are the high-<br>est level c low potential of 1.30 V vs. RHE at 10 mA  $\cdot$  cm<sup>2</sup> as<br>well as much high Faradaic efficiency (FE) for FDCA<br>(99.4%) even at 1.52 V vs. RHE, which are the high-<br>est level compared with the reported electrocatalysts.<br>Based o 30 V vs. RHE at 10 mA  $\cdot$  cm<sup>2</sup> as<br>
Faradaic efficiency (FE) for FDCA<br>
2 V vs. RHE, which are the high-<br>
with the reported electrocatalysts.<br>
CoAl-LDH-NSA, we constructed<br>
pled hydrogen generation system<br>
ell, which exhi well as much high Faradaic efficiency (FE) for FDCA<br>(99.4%) even at 1.52 V vs. RHE, which are the high-<br>est level compared with the reported electrocatalysts.<br>Based on the E-CoAl-LDH-NSA, we constructed<br>HMF oxidation coup (99.4%) even at 1.52 V vs. RHE, which are the highest level compared with the reported electrocatalysts.<br>Based on the E-CoAl-LDH-NSA, we constructed HMF oxidation coupled hydrogen generation system in a two-electrode cell est level compared with the reported electrocatalysts.<br>Based on the E-CoAl-LDH-NSA, we constructed<br>HMF oxidation coupled hydrogen generation system<br>in a two-electrode cell, which exhibited a low voltage<br>of 1.74 V to reach Based on the E-CoAl-LDH-NSA, we constructed HMF oxidation coupled hydrogen generation system<br>in a two-electrode cell, which exhibited a low voltage<br>of 1.74 V to reach 50 mA ·cm<sup>2</sup>, high H<sub>2</sub> yield of<br>44.16 L·h<sup>1</sup>·m<sup>2</sup> (4 HMF oxidation coupled hydrogen generation system<br>in a two-electrode cell, which exhibited a low voltage<br>of 1.74 V to reach 50 mA · cm<sup>2</sup>, high H<sub>2</sub> yield of<br>44.16 L·h<sup>1</sup>·m<sup>2</sup> (4 times higher than overall water<br>splitting) in a two-electrode cell, which exhibited a low voltage<br>of 1.74 V to reach 50 mA  $\cdot$  cm<sup>2</sup>, high H<sub>2</sub> yield of<br>44.16 L $\cdot$ h<sup>1</sup> $\cdot$ m<sup>2</sup> (4 times higher than overall water<br>splitting) as well as excellent stability. A hierar of 1.74 V to reach 50 mA  $\cdot$ cm<sup>2</sup>, high H<sub>2</sub> yield of 44.16 L $\cdot$ h<sup>1</sup> $\cdot$ m<sup>2</sup> (4 times higher than overall water splitting) as well as excellent stability. A hierarchical CoNi-LDHs with abundant Ni vacancies (VNi-CoNi-LD 44.16 L·h<sup>-1</sup>·m<sup>2</sup> (4 times higher than overall water splitting) as well as excellent stability. A hierarchical CoNi-LDHs with abundant Ni vacancies (VNi-CoNi-LDH) was reported by our group, which exhibited superior activ splitting) as well as excellent stability. A hierarchical<br>CoNi-LDHs with abundant Ni vacancies (VNi-CoNi-<br>LDH) was reported by our group, which exhibited<br>superior activity for both anodic HMFOR and ca-<br>thodic HER<sup>[79]</sup>. Th CoNi-LDHs with abundant Ni vacancies (VNi-CoNi-<br>LDH) was reported by our group, which exhibited<br>superior activity for both anodic HMFOR and ca-<br>thodic HER<sup>[79]</sup>. The EHCO based on VNi-CoNi-LDH<br>successfully realized the co LDH) was reported by our group, which exhibited<br>superior activity for both anodic HMFOR and ca-<br>thodic HER<sup>[79]</sup>. The EHCO based on VNi-CoNi-LDH<br>successfully realized the continuous synthesis of<br>highly-pure FDCA and enhan superior activity for both anodic HMFOR and ca-<br>thodic HER<sup>[79]</sup>. The EHCO based on VNi-CoNi-LDH<br>successfully realized the continuous synthesis of<br>highly-pure FDCA and enhanced hydrogen produc-<br>tion (49.25 L·m<sup>2</sup>·h<sup>-1</sup>). thodic HER<sup>[79]</sup>. The EHCO based on VNi-CoNi-LDH<br>successfully realized the continuous synthesis of<br>highly-pure FDCA and enhanced hydrogen produc-<br>tion (49.25 L·m<sup>2</sup>·h<sup>-)</sup>. In order to further enhance the<br>bifunctional acti successfully realized the continuous synthesis of<br>highly-pure FDCA and enhanced hydrogen produc-<br>tion (49.25 L·m<sup>2</sup>·h<sup>-)</sup>. In order to further enhance the<br>bifunctional activity of LDH-based electrocatalyst for<br>both HMFOR highly-pure FDCA and enhanced hydrogen production (49.25 L·m<sup>2</sup>·h<sup>-1</sup>). In order to further enhance the bifunctional activity of LDH-based electrocatalyst for both HMFOR and HER, we prepared a bifunctional CoNiP nanosheet tion (49.25 L·m<sup>2</sup>·h<sup>-)</sup>. In order to further enhance the<br>bifunctional activity of LDH-based electrocatalyst for<br>both HMFOR and HER, we prepared a bifunctional<br>CoNiP nanosheet integrated electrode (CoNiP-NIE)<br>via a phosph bifunctional activity of LDH-based electrocatalyst for<br>both HMFOR and HER, we prepared a bifunctional<br>CoNiP nanoshect integrated electrode (CoNiP-NIE)<br>via a phosphidation process based on LDHs, which<br>shows the enhanced HE In activity of LDH-based electrocatalyst for<br>OR and HER, we prepared a bifunctional<br>uosheet integrated electrode (CoNiP-NIE)<br>phidation process based on LDHs, which<br>enhanced HER performance compared<br>LDH, while maintains it  $g \cdot h^{-1} \cdot m^{-2}$ ). The EHCO system even can be driven by 1 HMFOR and HER, we prepared a bifunctional<br>siP nanosheet integrated electrode (CoNiP-NIE)<br>a phosphidation process based on LDHs, which<br>ws the enhanced HER performance compared<br>1 CoNi-LDH, while maintains its HMFOR perfor CoNiP nanosheet integrated electrode (CoNiP-NIE)<br>via a phosphidation process based on LDHs, which<br>shows the enhanced HER performance compared<br>with CoNi-LDH, while maintains its HMFOR perfor-<br>mance (Figure 5c)<sup>[89]</sup>. The o 电化学(*J. Electrochem.*) 2022, 28(10), 2214008 (8 of 18)<br> **e** between two elec-<br>
tion (Figure 5b)<sup>[57]</sup>. The *in-situ* exfoliation strategy<br>
distance between two introduces abundant oxygen vacancies on the CoAl-<br>
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 $# \# \# (J. \text{Electrochem.}) 2022, 28(10), 2214008 (9 of 18)$ <br>so lar-to-FDCA and 5.5% of solar-to-H<sub>2</sub> conversion most reported electrocatalysts. Based on above<br>efficiency.<br>In addition to electrochemical hydrogen evolution pled with gly <sup>EL</sup>{*E\\iffer CLU*} Exectrochemical 2022, 28(10), 2214008 (9 of 18)<br>
Iar-to-FDCA and 5.5% of solar-to-H<sub>2</sub> conversion most reported electrocatalysts. Based on above re-<br>
iciency.<br>
In addition to electrochemical hydrogen **E(E)** *Electrochem*.) 2022, 28(10), 2214008 (9 of 18)<br>
so lar-to-FDCA and 5.5% of solar-to-H<sub>2</sub> conversion most reported electrocatalysts. Based on above re-<br>
efficiency.<br>
In addition to electrochemical hydrogen evoluti **EMPECA** and 5.5% of solar-to-H<sub>1</sub> conversion and the set allows (9 of 18)<br>
so lar-to-FDCA and 5.5% of solar-to-H<sub>1</sub> conversion most reported electrocatalysts. Based on above re-<br>
efficiency.<br>
In addition to electrochemi the the constructed and 5.5% of solar-to-H) conversion<br>solar-to-FDCA and 5.5% of solar-to-H<sub>2</sub> conversion most reported electrocatalysts. Based on above re-<br>efficiency.<br>In addition to electrochemical hydrogen evolution a **EVACUTE 1200** Retraction, and carrier of CNS and state of the supported CoPt supported CoPt nanoparticles (CNS@CoPt and divious of the nanoparticle coupled with HMF oxidation, our group further de-<br>sults, we then constru **EVALUATION EXAMORET CONSTRANS (FIGURE ALTER)**<br> **EVALUAT SOMET AND SOLUTE SOME ALTER CONSTRANS (FOR ALTER)**<br> **EVALUAT SOMET AND SOLUTE ACT CONSTRANS (FIGURE ALTER)**<br> **EVALUAT AND CONSTRANS COPER CONSTRANS (FIGURE ALTER)**<br>  $\text{\textbf{E.}}(X, Electrowe, \textit{in}) \xspace{120} \text{C.} (X, \textit{in}) \xspace{120} \text{C.}$ to fit *F* is *n* to reach a current density of 19.1 m in the references and a current density of 19.1 m/s and a current density of  $\mathbb{R}$  must a current density of  $\mathbb{R}$  and the reach a current density of  $\mathbb{R}$   $\pm \frac{1}{2}$  for  $\pm \frac{1}{2}$  for  $\pm \frac{1}{2}$  for  $\pm \frac{1}{2}$  for  $\pm \frac{1}{2}$  and small onter the reference of the small on the reference of the small on the potential photon to electrochemical hydrogen evolution countinuo **respectively,** *Electrochem*, 2022, 28(10), 2214008 (9 of 18)<br>
so lar-to-FDCA and 5.5% of solar-to-H<sub>2</sub> conversion most reported electrocatalysts. Based on above re-<br>
efficiency,<br>
In addition to electrochemical hydrogen 28(10), 2214008 (9 of 18)<br>most reported electrocatalysts. Based on above re-<br>sults, we then constructed a hydrogen evolution cou-<br>pled with glycerol oxidation system with CNs@CoPt<br>as a bifunctional electrode. Surprisingly, 28(10), 2214008 (9 of 18)<br>most reported electrocatalysts. Based on above re-<br>sults, we then constructed a hydrogen evolution cou-<br>pled with glycerol oxidation system with CNs@CoPt<br>as a bifunctional electrode. Surprisingly 28(10), 2214008 (9 of 18)<br>most reported electrocatalysts. Based on above re-<br>sults, we then constructed a hydrogen evolution cou-<br>pled with glycerol oxidation system with CNs@CoPt<br>as a bifunctional electrode. Surprisingly 28(10), 2214008 (9 of 18)<br>
most reported electrocatalysts. Based on above re-<br>
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as a bifunctional electrode. Surprisi 28(10), 2214008 (9 of 18)<br>
most reported electrocatalysts. Based on above re-<br>
sults, we then constructed a hydrogen evolution cou-<br>
pled with glycerol oxidation system with CNs@CoPt<br>
as a bifunctional electrode. Surprisi 28(10), 2214008 (9 of 18)<br>most reported electrocatalysts. Based on above re-<br>sults, we then constructed a hydrogen evolution cou-<br>pled with glycerol oxidation system with CNs@CoPt<br>as a bifunctional electrode. Surprisingly atalysts. Based on above re-<br>ted a hydrogen evolution cou-<br>ation system with CNs@CoPt<br>de. Surprisingly, this coupling<br>matically enhanced hydrogen<br> $^{-1} \cdot m^{-2}$ ) in a cathode, larger than<br>ng system  $(27 \text{ L} \cdot \text{h}^{-1} \cdot m^{-2})$ 28(10), 2214008 (9 of 18)<br>most reported electrocatalysts. Based on above re-<br>sults, we then constructed a hydrogen evolution cou-<br>pled with glycerol oxidation system with CNs@CoPt<br>as a bifunctional electrode. Surprisingly above re-<br>
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most reported electrocatalysts. Based on above re-<br>
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pled with glycerol oxidation system with CNs@CoPt<br>
as a bifunctional electrode. Surprisi  $\frac{\text{d} \mathcal{H}}{\text{d} \mathcal{H}}$  (*J. Electrochem.*) 2022, 28(10), 2214008 (9 of 18)<br>solar-to-H<sub>2</sub> conversion most reported electrocatalysts. Based on above results, we then constructed a hydrogen evolution cou-<br>all hydrogen ev



 $\# \ell \#$  (*J. Electrochem.*) 2022, 28(10), 2214008 (10 of 18)<br>Given that, Duan and co-workers synthesized a coop-<br>orative electrocatalyst of Au nanoparticles supported<br>production from water electrolysis. Meanwhile, sun-<br>o  $#E\# (J. Electrochem.) 2022, 28(10), 2214008 (10 of 18)$ <br>
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Given that, Duan and co-workers synthesized a coop-<br>
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erative electrocatalyst of Au nanoparticles supported <sup>EL</sup><sup>{{}}</sup>(*J. Electrochem.*) 2022, 28(10), 2214008 (10 of 18)<br>
Given that, Duan and co-workers synthesized a coop-<br>
tric nanogenerator (TENG), thus realizing hydrogen<br>
erative electrocatalyst of Au nanoparticles supporte hol oxidation at high current density (Figure 5e)[81]  $\frac{E}{E}$  (*L Electrochem.*) 2022, 28(10), 2214008 (10 of 18)<br>
Given that, Duan and co-workers synthesized a coop-<br>
trie nanogenerator (TENG), thus realizing hydrogen<br>
erative electrocatalyst of Au nanoparticles support riched at Au/CoOOH interface, thus is easily oxi- $4E\%$  (*L Electrochem.*) 2022, 28(10), 2214008 (10 of 18)<br>
Given that, Duan and co-workers synthesized a coop-<br>
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p **EVALUATION EXAMORE (EXAMORENT:** The dimension of t **HEVALUA** Electroshem.) 2022, 28(10), 2214008 (10 of 18)<br>
Given that, Duan and co-workers synthesized a coop-<br>
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pro  $\#E\mathcal{F}(L\text{ *Electrochem.}) 2022, 28(10), 2214008 (10 of 18)*$ <br>Given that, Duan and co-workers synthesized a coop-<br>trie nanogenerator (TENG), thus realizing hydrogen<br>erative electrocatalyst of Au nanoparticles supported<br>production 1.3V and 1.5 V vs. RHE, respectively, representing **EVALUATI EVALUATIVE CONTING (FOR A SET ALCONS** (10 of 18)<br> **EGIVED INTEREV** (FOR A THE analogon and co-workers supported and coop-<br>
intermal external temperature electrophysis. Meanwhile, summand<br>
conduction filter analo  $\frac{1}{2}$  ( $\frac{1}{2}$ ,  $\pm \frac{1}{2}E \neq (LEertochem.)$  2022, 28(10), 2214008 (10 of 18)<br>Given that, Duan and co-workers synthesized a coop-<br>rative electrocatalyst of Au nanoparticles supported<br>production from water electrolysis. Meanwhile, sun-<br>on cobalt drogen production rate reached 3.19 mmol  $\cdot$ cm<sup>2</sup> $\cdot$ h<sup>-1</sup> spectively, resulting a STH efficiency of ~13% and a Given that, Duan and co-workers synthesized a coop-<br>
Firstive electrocatalyst of Au nanoparticles supported<br>
on cobalt oxyhydroxide nanosheets (Au/CoOOH), light, low-grade waste heat<br>
which realizes superior performance f Given that, Duan and co-workers synthesized a coop-<br>tric nanogenerator (TENG), thus realizing hydrogen<br>entire electrocatalyst of Au ananoparties supported<br>on costal coxyhytroxide nanosheets (Au/CoOOH), light, low-grade wa erative electrocatalyst of Au nanoparticles supported<br>
production from water electrolysis. Meanwhile, sun-<br>
on coolal oxyhytoxide nanoshests (AAU<sup>C</sup>OOOH), light, low-grade waste heat or natural temperature<br>
which realizes on cobalt oxyhytroxide nanosheets (Au/CoOOH), light, low-grade waste heat or natural temperature<br>which realizes superfor preformance for benzyl alco-<br>chemicalizes superfor performance for benzyl alcohol is en-<br>electrocity which realizes superior performance for benzyl alco-<br>
bota coidation at high current density (Figure 5)<sup>[16]</sup>. electricity(TE<sub>2</sub>), offering an alternative external enci-<br>
Deep studies reveal that the benzyl dicolol is enhol oxidation at high current density (Figure 5e)<sup>na</sup>. electricity (TE), offering an alternative external encre-<br>Deep studies reveal that the benzyl alcohol is en-<br>
gy to powered at AuCoGOH interface, thus is easily oxi-<br> Deep studies reveal that the benzyl alcohol is en-<br>
gy to power water electrophysis.<br>
reched at Au/CoOOH interface, thus is easily oxi-<br>
duction diverse ligine and reflection and reaction of the state of the state of the riched at Au/CoOOH interface, thus is easily oxi-<br>
drong various green energy powered water electrocoly<br>
drop the electrophilic OHF generated on CoOOH corresponds, solar powered water electroly<br>
with low reaction barrier, dized by the electrophilic OH\* generated on CoOOH trolysis systems, solar powered water electrolysis systems<br>with low reach the hard or hard of the mat have been widely designed and applied owing<br>than pure Au. The Au/CoOO

units were also reformed to benzoate and adipate<br>
win high yields (91.271 V) was employed to power<br>
with high yields (91.2%). AME coll, compassion (SDM)<br>
2.4 Integrating with Renewable Energy<br>
2.4 Integrating with Renewab

28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity b  $28(10)$ ,  $2214008(10 \text{ of } 18)$ <br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electri  $28(10)$ ,  $2214008(10 \text{ of } 18)$ <br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electri 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity b 28(10), 2214008 (10 of 18)<br>
tric nanogenerator (TENG), thus realizing hydrogen<br>
production from water electrolysis. Meanwhile, sun-<br>
light, low-grade waste heat or natural temperature<br>
changes can be converted to electrici  $28(10)$ ,  $2214008$  (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electric (10), 2214008 (10 of 18)<br>
c nanogenerator (TENG), thus realizing hydrogen<br>
oduction from water electrolysis. Meanwhile, sun-<br>
ht, low-grade waste heat or natural temperature<br>
amges can be converted to electricity by thermo 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity b 电化学(*J. Electrochem.*) 2022, 28(10), 2214008 (10 of 18)<br>
rs synthesized a coop-<br>
inconsisted a coop-<br>
inconsisted by the moderator (TENG), thus realizing hydrogen<br>
inconsitions are production from water electrolysis. Mean

The converties suppression of the managementator (TENG), thus realizing hydrogen<br>of Au nanoparticles supprediction from water electrolysis. Meanwhile, sun-<br>of Au nanoparticles supprediction from water leetrolysis. Meanwhi with low reaction barrier, leading to higher activity<br>them have been widely designed and applied owing<br>than pure Au. The Au/CoOM exhibited the current to their convenience, simplicity and high stability.<br>densities of 340 than purc Au. The Au/CoOOH exhibited the current to their convenience, simplicity and high stability.<br>
densities of 340 and 540 mA - cm<sup>2</sup> at potential of However, the hydrogen production from this technol-<br>
1.3V and 1.5V densities of 340 and 540 mA  $\cdot$ cm<sup>2</sup> at potential of However, the hydrogen production from this technol-<br>1.3V and 1.5 V vs. RHE, respectively, representing ogy is still limited by price and efficiency factors.<br>
Moreover, 1.3V and 1.5 V vs. RHE, respectively, representing ogy is still limited by price and efficiency fa<br>
the highest current density value reported so far. Currently, the efficiencies of industrial AWE sy<br>
Moreover, the benefi the highest current density value reported so far. Currently, the efficiencies of industrial AWE systems<br>Moreover, the benzyl alcohol conversion rate and hy-<br>end mainstrams nolar parals are -70% and -18%, re-<br>drogen produ or<br>cover, the benzyl alcohol conversion rate and hy-<br>
and mainstream solar panels are -70% and -18%, re-<br>
18% renewable contained 3.19 mmol - m<sup>2</sup> - hy spectively, are the potential<br>
117.9 mL - cm<sup>2</sup> - hy respectively, at drogen production rate reached 3.19 mmol·cm<sup>2</sup>·h<sup>1</sup> spectively, resulting a STH efficiency of ~13% and a<br>
and 11.3.9 mL-cm<sup>2</sup>·h<sup>2</sup>, respectively, at the potential hydrogen cost of ~10S-kg<sup>1</sup>. Based on this, Zhao and<br>
of 1 and 117.9 mL - cm<sup>2</sup> - h<sup>1</sup>, respectively, at the potential hydrogen cost of -10S - kg<sup>-</sup>. Based on this, Zhao and f1.3 V vs. RHE, which is 26- and 28-5-0d higher co-workers presented a direct solar power<br>than that of Al. of 1.3 V vs. RHE, which is 26- and 28-fold higher<br>co-workers presented a direct solar powered AWE<br>than that of Au. Furthermore, Duan and co-workers system through coupling NiMo hydrogen evolution<br>developed a MnCoOOH elect than that of Au. Furthermore, Duan and co-workers<br>
eystem through coupling NiMo hydrogen evolution<br>
developed a MnCoOH electrocatalyst and the effectence day end evolution<br>
depending of lignin-derived secondary alcohols o developed a MnCoOOH electrocatalyst for efficient electrocatalyst and NiFe-hased oxygen evolution<br>upgrading of lignin-deviced secondary alcohols or ke- electrocatalyst with high-performance peroveskite-Si<br>tones into earbo upgrading of lignin-derived secondary alcobols or ke-<br>electrocatalyst with high-performance perovskite-Si<br>conscinto carboxylates coupling with hydrogen pro-<br>tandem cells (Figure 6b<sup>jm2</sup>). The vyield and operational 10 on<br> tones into carboxylates coupling with hydrogen pro-<br>
tandem cells (Figure 6b)<sup>991</sup>. The overpotential to drive<br>
duction (Figure 5f)<sup>991</sup>. The yield and operational 10 mA - cm<sup>3</sup> over NiMo electrocatalyst was only 6<br>
ducti duction (Figure 5f)<sup>(80)</sup>. The yield and operational 10 mA -cm<sup>2</sup> over NiMo clectrocatalyst was only 6<br>stability for acloobis and kctons to corresponding mV. After coupling with Nife-based oxygen colu-<br>carboxylates over M stability for alcohols and ketones to corresponding<br>
mV. After coupling with NiFe-based oxygen evolu-<br>
can box of Coro Corol could reach to 64% ~ to not cletrocalizy the potential of orien's<br>
99% and 200 h. As proof of co earboxylates over MnCoOOH could reach to  $64\%$  - tion electrocatalyst, the potential to drive 10 mA  $\cdot$  com-<br>29% and 200 h. As proof of concept, diverse lignin was 1.48 V and the stability for overall wate split-<br>around 99% and 200 h. As proof of concept, diverse lignin was 1.48 V and the stability for overall water split-<br>aromatics and KA oil featuring C(OH)-C and C(O)-C imp reached 100 h. A perovskite solar cell with high aromatics and aromatics and KA oil featuring C(OII)-C and C(O)-C<br>
ing reached 100 h. A perovskite solar cell with high<br>
units were also reformed to benzonte and adipate<br>
with high yields (91.3% and 64.2%).<br> **2.4 Integrating with Renewa** 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity b 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity 28(10), 2214008 (10 of 18)<br>
tric nanogenerator (TENG), thus realizing hydrogen<br>
production from water electrolysis. Meanwhile, sun-<br>
light, low-grade waste heat or natural temperature<br>
changes can be converted to electric 28(10), 2214008 (10 of 18)<br>
tric nanogenerator (TENG), thus realizing hydrogen<br>
production from water electrolysis. Meanwhile, sun-<br>
light, low-grade waste heat or natural temperature<br>
changes can be converted to electric 28(10), 2214008 (10 of 18)<br>tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity Lettry, 221 Noo (1.0 a.16)<br>
tric nanogenerator (TENG), thus realizing hydrogen<br>
production from water electrolysis. Meanwhile, sun-<br>
light, low-grade waste heat or natural temperature<br>
changes can be converted to electri tric nanogenerator (TENG), thus realizing hydrogen<br>production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity by thermo-<br>electricity (TE) production from water electrolysis. Meanwhile, sun-<br>light, low-grade waste heat or natural temperature<br>changes can be converted to electricity by thermo-<br>electricity (TE), offering an alternative external energy<br>to power light, low-grade waste heat or natural temperature<br>changes can be converted to electricity by thermo-<br>electricity (TE), offering an alternative external ener-<br>gy to power water electrolysis.<br>Among various green energy pow changes can be converted to electricity by thermo-<br>electricity (TE), offering an alternative external ener-<br>gy to power water electrolysis.<br>Among various green energy powered water electrolysis systems<br>have been widely de electricity (TE), offering an alternative external energy to power water electrolysis.<br>
Among various green energy powered water electrolysis systems have been widely designed and applied owing to their convenience, simpl gy to power water electrolysis.<br>
Among various green energy powered water electrolysis systems, solar powered water electrolysis systems have been widely designed and applied owing to their convenience, simplicity and hig Among various green energy powered water electrolysis systems, solar powered water electrolysis systems have been widely designed and applied owing to their convenience, simplicity and high stability. However, the hydroge trolysis systems, solar powered water electrolysis sys-<br>tems have been widely designed and applied owing<br>to their convenience, simplicity and high stability.<br>However, the hydrogen production from this technol-<br>ogy is stil to their convenience, simplicity and high stability.<br>However, the hydrogen production from this technol-<br>ogy is still limited by price and efficiency factors.<br>Currently, the efficiencies of industrial AWE systems<br>and main However, the hydrogen production from this technology is still limited by price and efficiency factors.<br>Currently, the efficiencies of industrial AWE systems and mainstream solar panels are  $\sim 70\%$  and  $\sim 18\%$ , respec ogy is still limited by price and efficiency factors.<br>Currently, the efficiencies of industrial AWE systems<br>and mainstream solar panels are ~70% and ~18%, re-<br>spectively, resulting a STH efficiency of ~13% and a<br>hydrogen Currently, the efficiencies of industrial AWE systems<br>and mainstream solar panels are ~70% and ~18%, re-<br>spectively, resulting a STH efficiency of ~13% and a<br>hydrogen cost of ~10\$ ·kg<sup>-1</sup>. Based on this, Zhao and<br>co-worke and mainstream solar panels are ~70% and ~18%, respectively, resulting a STH efficiency of ~13% and a hydrogen cost of ~10\$ ·kg<sup>-1</sup>. Based on this, Zhao and co-workers presented a direct solar powered AWE system through c spectively, resulting a STH efficiency of ~13% and a<br>hydrogen cost of ~10\$ ·kg<sup>-1</sup>. Based on this, Zhao and<br>co-workers presented a direct solar powered AWE<br>system through coupling NiMo hydrogen evolution<br>electrocatalyst a hydrogen cost of ~10\$ · kg<sup>-1</sup>. Based on this, Zhao and<br>co-workers presented a direct solar powered AWE<br>system through coupling NiMo hydrogen evolution<br>electrocatalyst and NiFe-based oxygen evolution<br>electrocatalyst with co-workers presented a direct solar powered AWE<br>system through coupling NiMo hydrogen evolution<br>electrocatalyst and NiFe-based oxygen evolution<br>electrocatalyst with high-performance perovskite-Si<br>tandem cells (Figure 6b)<sup></sup> system through coupling NiMo hydrogen evolution<br>electrocatalyst and NiFe-based oxygen evolution<br>electrocatalyst with high-performance perovskite-Si<br>tandem cells (Figure 6b)<sup>88)</sup>. The overpotential to drive<br>10 mA  $\cdot$  cm<sup>-</sup> electrocatalyst and NiFe-based oxygen evolution<br>electrocatalyst with high-performance perovskite-Si<br>tandem cells (Figure 6b)<sup>881</sup>. The overpotential to drive<br>10 mA ·cm<sup>-2</sup> over NiMo electrocatalyst was only 6<br>mV. After co electrocatalyst with high-performance perovskite-Si<br>tandem cells (Figure 6b)<sup>881</sup>. The overpotential to drive<br>10 mA  $\cdot$ cm<sup>2</sup> over NiMo electrocatalyst was only 6<br>mV. After coupling with NiFe-based oxygen evolu-<br>tion elec tandem cells (Figure 6b)<sup>883</sup>. The overpotential to drive 10 mA  $\cdot$ cm<sup>2</sup> over NiMo electrocatalyst was only 6 mV. After coupling with NiFe-based oxygen evolution electrocatalyst, the potential to drive 10 mA $\cdot$ cm<sup>2</sup> was 10 mA  $\cdot$ cm<sup>2</sup> over NiMo electrocatalyst was only 6<br>mV. After coupling with NiFe-based oxygen evolu-<br>tion electrocatalyst, the potential to drive 10 mA $\cdot$ cm<sup>2</sup><br>was 1.48 V and the stability for overall water split-<br>ting mV. After coupling with NiFe-based oxygen evolution electrocatalyst, the potential to drive 10 mA·cm<sup>2</sup> was 1.48 V and the stability for overall water splitting reached 100 h. A perovskite solar cell with high open circui n electrocatalyst, the potential to drive 10 mA  $\cdot$  cm<sup>2</sup><br>s 1.48 V and the stability for overall water split-<br>g reached 100 h. A perovskite solar cell with high<br>en circuit voltage (1.271 V) was employed to power<br>WE cell, was 1.48 V and the stability for overall water split-<br>ting reached 100 h. A perovskite solar cell with high<br>open circuit voltage (1.271 V) was employed to power<br>AWE cell, exhibiting a high solar-to-hydrogen (STH)<br>efficien ting reached 100 h. A perovskite solar cell with high<br>open circuit voltage (1.271 V) was employed to power<br>AWE cell, exhibiting a high solar-to-hydrogen (STH)<br>efficiency (20.01%) and fulfilling the 2020 DOE tar-<br>get. The open circuit voltage (1.271 V) was employed to power<br>AWE cell, exhibiting a high solar-to-hydrogen (STH)<br>efficiency (20.01%) and fulfilling the 2020 DOE tar-<br>get. The STH efficiency could be increased to 25%<br>after optimiz

 $\mathbb{E} \mathcal{H} \cong (L \text{ Electrochem.}) 2022, 28(10), 2214008 (11 of 18)$ <br>which effectively resolve the conflicts between solar mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>cells and electrocatalysts. Based on this, Zhou and 600 r then the discrete matrices and the discrepancy of TENG reaching<br>which effectively resolve the conflicts between solar mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>cells and electrocatalysts. Based on this, Zhou an the  $\mathcal{C}_L$  Electrochem.) 2022, 28(10), 2214008 (11 of 18)<br>
which effectively resolve the conflicts between solar<br>
co-workers proposed a TE device composed of multi-min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
co-**EVALUATION**<br> **EVALUATION**<br> **EVALUATION** (Figure 6d)[95]. The Ni nanosheets array grown on the  $\frac{4E\#(I. Electrow, B)}{4E}$  and detrocatalytis. Based on this,  $2022, 28(10), 2214008 (11 of 18)$ <br>
which effectively resolve conflicts between solar mL-min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
cells and electrocatalysts.  $\#E\#(L \text{ Alexanderm})$  2022, 28(10), 2214008 (11 of 18)<br>which effectively resolve the conflicts between solar mL-min<sup>-1</sup>, with the spinning speed of TENG reaching<br>cells and electrocatalysts. Based on this, Zhou and 600 r-min<sup>-1</sup> **ENALA THE SET AS THE CONDUCT THE THE SET AND THE SET AN THE SET AND THE SET EVALUATION 1989**<br> **EVALUATION** (11 of 18)<br> **EVALUATION** CHECT TRIG TENG TERRIFIES by the conflicts between solar<br>
and this, Zhou and  $600 \text{ r-min}^4$ , Mortower, the TENG could be driven by<br>
co-workers proposed a TE device c **EVALUATION THE SET ALTERT CONSTRANT (THE SET ALTERT ALTERT AND THE SET ALTERT AND THE SET ALTERT AND THE SET AND EXALUATE (1. Electrocheme**) 2022, 28(10), 2214008 (11 of 18)<br>
which effectively resolve the conflicts between solar mL-min<sup>4</sup>, with the spinning speed of TENG reaching<br>
cells and electrocatalysts. Based on this, Zhou and **EVALUAT Example 10.12** (*B. B.Coronchem,* 2022, 28(10), 2214008 (11 of 18)<br>
which effectively resolve the conflicts between solar mL-min<sup>1</sup>, with the spinning speed of TENG reaching<br>
cells and electrocatalysts. Based on the  $\frac{1}{2}$  the  $\frac{1}{2}$  (*LE-terrochem*, 2022, 28(10), 2214008 (11 of 18)<br>
which effectively resolve the conflicts between solar mt. min<sup>-1</sup>, with the spinning speed of TFNG reaching<br>
cells and electrocatalysts. Based mmol · h<sup>-1</sup>. Furthermore, Bowen and co-workers uti- $\frac{10}{2}$  (Electrocal be complicated and the simulate production of a TENG reaching speed of TENG reaching<br>dectrocatalysts. Based on this, Zhou and 600 r·min<sup>-1</sup>, with the spinning speed of TENG reaching the feltroceatal **EVALUAT THE CONSERVAL CONSERVALUAT THE CONSERVALUAT THE SET (FREQUEST).** Which effectively resolve the conflicts between solar mL-min<sup>1</sup>, with the spinning speed of TENG reaching cells and electrocatalysts. Based on this which effectively resolve the condities between solar<br>
which effectively resolve the condities between solar<br>
cells and electrocatalysts. Based on this, Zhou and<br>
600 r-min<sup>+</sup>, whit the spinning speed of TENG reaching<br>
co which effectively resolve the conflicts between solar mL-min<sup>2</sup>, with the spinning speed of TENG reaching<br>ecl. Solar decletrocatally as. Based on this; Zhou and 600 r-min<sup>2</sup>. Moreover, the TENG could be thiven by<br>eo-worke cells and electrocatalysts. Based on this, Zhou and 600 r·min<sup>-1</sup>. Moreover, the TFNG could be driven by<br>co-workers proposed a TE device composed of multi-<br>the flow of normal tap water, demonstrating the fluid<br>fractional N co-workers proposed a TF. device composed of multi-<br>the flow of normal tap water, demonstrating the fully<br>finductional Ni nanosheets array to power AWE system self-powered equability. The above works have initi-<br>firigure functional Ni nanosheets array to power AWE system self-powered capability. The above works have initi-<br>(Figure 60<sup>ym</sup>): The Ni annoshests array grown on the and a research direction in the field of TENG-driven<br>bot side o (Figure 6d)<sup>861</sup>. The Ni nanosheets array grown on the ated a research direction in the field of TENG-drive<br>of the side of photosthermore with a rate are all to the photosthermore difference and conversion layer to provid tinuous hydrogen with a rate of 0.655  $\mu$ mol $\cdot$ h<sup>-1</sup>. The performance of AWE for hydrogen production t side of TE device can play the role of photother-<br>
a conversion layer to provide temperature different entities<br>
ce for TE, and active electroceatalysts for HER. As<br>
type the world, and exploring water electrolysis for<br> mal conversion layer to provide temperature differ-<br>accessor and **Outlooks**<br>core for Fig. and active electrocatalysts for HER. As a Hydrogen has received extensive attention from all<br>a result, the Ni manosheets array exhi ence for TF, and active electrocatalysts for HFR. As<br>
are result, the Yin marsheets array exhibited a low<br>
overpotential of 173 mV at a current density of 10<br>
overpotential of 173 mV at a current density of 10<br>
mA  $\cdot$  cm a result, the Ni nanosheets array exhibited a low over the world, and exploring water electrolysis for overgrotential of 173 mV at a current density of 10 industrial hydrogen production is one of the most overgretental of overpotential of 173 mV at a current density of 10<br>
mdustrial hydrogen production is one of the mest<br>
mA - em<sup>2</sup> and superior stability of 20 h. The TE promising works today. In this review, we present a<br>
movered AWE syst mA  $\cdot$  cm<sup>2</sup> and superior stability of 20 h. The TF<br>promising works today. In this review, we present a<br>powered AWE from the<br>delivered as high hydrogen production rate of 1.818<br>perpections of electrocatalyst, reaction an

 $8(10)$ , 2214008 (11 of 18)<br>mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>the flow of normal tap water, demonstrating the fully<br>self-powered capability. The abov  $8(10)$ , 2214008 (11 of 18)<br>mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>the flow of normal tap water, demonstrating the fully<br>self-powered capability. The abov  $8(10)$ , 2214008 (11 of 18)<br>
mL  $\cdot$  min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600  $\rm{r} \cdot \rm{min}^{-1}$ . Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered cap  $s(10)$ , 2214008 (11 of 18)<br>
mL · min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r · min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capability.  $\frac{8(10)}{2214008(11 \text{ of } 18)}$ <br>
mL · min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r · min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capabilit  $8(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capability. The  $8(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capability. The 0, 2214008 (11 of 18)<br>  $L$ -min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
0 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>  $\frac{1}{2}$  flow of normal tap water, demonstrating the fully<br>  $\frac{1}{2}$  flowered capability.  $x_{\text{N}}$  (10), 2214008 (11 of 18)<br>
mL · min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r· min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capabi 电化学(*J. Electrochem.*) 2022, 28(10), 2214008 (11 of 18)<br>
conflicts between solar mL ·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
sed on this, Zhou and 600 r ·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
vi

 $8(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the filly<br>
self-powered capability. The  $8(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the filly<br>
self-powered capability. The  $(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capability. The a  $8(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capability. The  $8(10)$ , 2214008 (11 of 18)<br>
mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capability. The  $\frac{8(10)}{2214008}$  (11 of 18)<br>
mL · min<sup>-1</sup>, with the spinning speed of TENG reaching<br>
600 r · min<sup>-1</sup>. Moreover, the TENG could be driven by<br>
the flow of normal tap water, demonstrating the fully<br>
self-powered capabilit mL  $\cdot$ min<sup>-1</sup>, with the spinning speed of TENG reaching<br>600  $\cdot$   $\cdot$ min<sup>-1</sup>. Moreover, the TENG could be driven by<br>the flow of normal tap water, demonstrating the fully<br>self-powered capability. The above works have init mL·min<sup>-1</sup>, with the spinning speed of TENG reaching<br>600 r·min<sup>-1</sup>. Moreover, the TENG could be driven by<br>the flow of normal tap water, demonstrating the fully<br>self-powered capability. The above works have initi-<br>ated a re 600  $r \cdot min^{-1}$ . Moreover, the TENG could be driven by<br>the flow of normal tap water, demonstrating the fully<br>self-powered capability. The above works have initi-<br>ated a research direction in the field of TENG-driven<br>AWE in the flow of normal tap water, demonstrating the fully<br>self-powered capability. The above works have initi-<br>ated a research direction in the field of TENG-driven<br>AWE in general.<br>**3 Conclusions and Outlooks**<br>Hydrogen has r (1) If-powered capability. The above works have initi-<br>d a research direction in the field of TENG-driven<br>ME in general.<br>**Conclusions and Outlooks**<br>Hydrogen has received extensive attention from all<br>er the world, and explo ided a research direction in the field of TENG-driven<br>WE in general.<br>**Conclusions and Outlooks**<br>Hydrogen has received extensive attention from all<br>er the world, and exploring water electrolysis for<br>dustrial hydrogen produc AWE in general.<br> **3 Conclusions and Outlooks**<br>
Hydrogen has received extensive attention from all<br>
over the world, and exploring water electrolysis for<br>
industrial hydrogen production is one of the most<br>
promising works to **3 Conclusions and Outlooks**<br>
Hydrogen has received extensive attention from all<br>
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industrial hydrogen production is one of the most<br>
promising works today. In this revi Hydrogen has received extensive attention from all<br>over the world, and exploring water electrolysis for<br>industrial hydrogen production is one of the most<br>promising works today. In this review, we present a<br>comprehensive re over the world, and exploring water electrolysis for<br>industrial hydrogen production is one of the most<br>promising works today. In this review, we present a<br>comprehensive review on advances in AWE from the<br>perspectives of el industrial hydrogen production is one of the most<br>promising works today. In this review, we present a<br>comprehensive review on advances in AWE from the<br>perspectives of electrocatalyst, reaction and system.<br>Despite many impo

powered AWE system was then constructed, which<br>
comprehensive review on advances in AWE from the<br>
delivered a high hydrogen production rate of 1.818<br>
mmol·h<sup>1</sup><sub>i</sub> Furthermore, Bowen and co-workers uti-<br>
Despite many import delivered a high hydrogen production rate of 1.818<br>
memory hrv Eurothermote, Bowen and co-workers uti-<br>
Einzel irrange image important developments of hydrogen<br>
lized lead zirconate titanate as an external charge<br>
go in th mmol ·h<sup>3</sup>. Furthermore, Bowen and eo-workers uti-<br>lizely lead riveonate times as an external charge production from AWE, there are still a long way to<br>isource to generate tinestate as an external charge groduction from A lized lead ziroonate titanate as an external charge<br>
production from AWE, there are still a long way to<br>
source to generate electricity through undergoing<br>
so in the view of industrial applications because of<br>
folo-cold t source to generate electricity through undergoing<br>
go in the view of industrial applications because of<br>
bot-cold thermal cycles, which exhibited an anximum high production cost and low energy efficiency. In<br>
bot-cold the hot-cold thermal cycles, which exhibited a maximum<br>
high production cost and low energy efficiency. In<br>
voltage of 2.34 V and micro-level current of  $\sim 7 \mu \Lambda$  order to promote the development of AWE, attention<br>
relige of voltage of 2.34 V and micro-level current of  $\sim$  7 μA order to promote the development of AWE, attention (Figure 6e<sup>yes)</sup>. Then, an AWE, system powered by py-<br>
reaching the position and the following spectes:<br>
(Figure 6 (Figure 6c)<sup>ns4</sup>. Then, an AWE system powered by pyschould be paid to the following aspects:<br>
realocterins was constructed, which can preduce con-<br>
tinuous hydrogen with a rate of 0.655 µmol-h<sup>1</sup>. The performance of AWE f roclearins was constructed, which can produce con-<br>
(1) Electrocatalyst/electrode<br>
imaxis hydrogen production<br>
imaxis hydrogen production<br>
imaxis hydrogen production<br>
imaxis important for the morphological structures of e tinuous hydrogen with a rate of 0.655  $\mu$ mol-h<sup>3</sup>.<br>
The performance of AWE for hydrogen production<br>
ment to power water electrolysis is important for the<br>
more stable green energy from environment to power water electrol 6.9685  $\mu$ L·min<sup>-1</sup> when the wind speed was 10 m·s<sup>-1</sup>, of electrocatalyst preparation, despite various synthet-Harvesting more stable green energy from environ-<br>
nent to power value of morphological structures of electronical yields in importing<br>
meta to power value relectronical structure<br>
Voltagence and phytopical protocological ment to power water electrolysis is important for the morphological structures of electrocatalyst. Through wides<br>preach application of hydrogen production. designing the appropriate surface interfacial structure<br>Compared widespread application of hydrogen production.<br>
colorgandge to solar energy, wind energy is independent and hydrophilic properties of integrated electrode, the<br>
Compared to solar energy, wind energy is independent of the Compared to solar energy, wind energy is independented and hydrophilic properties of integrated electrode, the helm of time, and even can generate electrivity 24 reaction efficiency and durability can be further im-<br>chour dent of time, and even can generate electricity 24 reaction efficiency and durability can be further im-<br>hours a day. Herein, Fan and co-workers employed a proved. However, the universal structure-activity re-<br>coaxial rot hours a day. Herein, Fan and co-workers employed a<br>
nowed. However, the universal structure-activity re-<br>
consided rotatory freestanding trivodectoric nanogener-<br>
ator (CRF-TFNG) to harvest wind energy for hydro-<br>
practic promising works today. In this review, we present a<br>comprehensive review on advances in AWE from the<br>perspectives of electrocatalyst, reaction and system.<br>Despite many important developments of hydrogen<br>production from AWE comprehensive review on advances in AWE from the<br>perspectives of electrocatalyst, reaction and system.<br>Despite many important developments of hydrogen<br>production from AWE, there are still a long way to<br>go in the view of i perspectives of electrocatalyst, reaction and system.<br>Despite many important developments of hydrogen<br>production from AWE, there are still a long way to<br>go in the view of industrial applications because of<br>high production Despite many important developments of hydrogen<br>production from AWE, there are still a long way to<br>go in the view of industrial applications because of<br>high production cost and low energy efficiency. In<br>order to promote t production from AWE, there are still a long way to<br>go in the view of industrial applications because of<br>high production cost and low energy efficiency. In<br>order to promote the development of AWE, attention<br>should be paid go in the view of industrial applications because of<br>high production cost and low energy efficiency. In<br>order to promote the development of AWE, attention<br>should be paid to the following aspects:<br>(1) Electrocatalyst/electr high production cost and low energy efficiency. In<br>order to promote the development of AWE, attention<br>should be paid to the following aspects:<br>(1) Electrocatalyst/electrode<br>The performance of AWE for hydrogen production<br>c order to promote the development of AWE, attention<br>should be paid to the following aspects:<br>(1) Electrocatalyst/electrode<br>The performance of AWE for hydrogen production<br>can be enhanced via regulating the electronic and<br>mor should be paid to the following aspects:<br>
(1) Electrocatalyst/electrode<br>
The performance of AWE for hydrogen production<br>
can be enhanced via regulating the electronic and<br>
morphological structures of electrocatalyst. Thro (1) Electrocatalyst/electrode<br>The performance of AWE for hydrogen production<br>can be enhanced via regulating the electronic and<br>morphological structures of electrocatalyst. Through<br>designing the appropriate surface interfa The performance of AWE for hydrogen production<br>can be enhanced via regulating the electronic and<br>morphological structures of electrocatalyst. Through<br>designing the appropriate surface interfacial structure<br>and hydrophilic can be enhanced via regulating the electronic and<br>morphological structures of electrocatalyst. Through<br>designing the appropriate surface interfacial structure<br>and hydrophilic properties of integrated electrode, the<br>reacti morphological structures of electrocatalyst. Through<br>designing the appropriate surface interfacial structure<br>and hydrophilic properties of integrated electrode, the<br>reaction efficiency and durability can be further im-<br>pro designing the appropriate surface interfacial structure<br>and hydrophilic properties of integrated electrode, the<br>reaction efficiency and durability can be further im-<br>proved. However, the universal structure-activity re-<br>la and hydrophilic properties of integrated electrode, the reaction efficiency and durability can be further im-<br>proved. However, the universal structure-activity re-<br>lationship to guide the electrocatalyst design is im-<br>prac reaction efficiency and durability can be further im-<br>proved. However, the universal structure-activity re-<br>lationship to guide the electrocatalyst design is im-<br>practical and contradictory. In addition, most report-<br>ed el proved. However, the universal structure-activity relationship to guide the electrocatalyst design is im-<br>practical and contradictory. In addition, most report-<br>ed electrocatalysts are unable to meet the require-<br>ments of



**Figure 6** (a) Schematic illustration of weter splitting powered by various green energy systems. (b) Schematic illustration, J-F curve of solar powered AWE system.<sup>30</sup>. Reproduced with permission of Ref. 81. Corporation Example 18 and the commercialization of water apliting persones are energy systems. (b) Schematic illustration of water splitting persones thy various grees are gy systems. (b) Schematic flustration of  $\theta$ . In addition, Figure 6 (a) Schematic illustration of water splitting powered by various green energy systems. (b) Schematic illustration, *H* various<br>and LSV eure of solar powered AWE system<sup>in</sup>. Reproduced with permission of Ref. 85, **Thursday and the system of the system of the system (a)** Schematic illustration of water splitting powered by various green energy systems. (b) Schematic illustration, *IV* curve of Schematic illustration of Her Space (s **Figure 6** (a) Schematic illustration of water splitting powered by various green energy systems. (b) Schematic illustration, *I-F* urve<br>and I-SV euroc of solar powered AWE system<sup>per</sup>, Reproduced with permission of Ref. 8 **Figure 6** (a) Schematic illustration of water splitting powered by various green energy systems. (b) Schematic and LSV curve of solar powered AWE system<sup>161</sup>. Reproduced with permission of Ref. 85, copyright Wiley. (c) S pare 6 (a) Schematic illustration of water splitting powered by various green energy systems. (b)<br>
LISV curve of solar powered AWE system<sup>(ss)</sup>. Reproduced with permission of Ref. 85, copyright<br>
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LSV curve of solar powered AWE system<sup>68</sup>. Repords covidt permission of Ref. S5, opyright Wiley: (e) Comparison in the conyright Newiro (e) Schematic of pyrocelectric as a external source of AWE system<sup>189</sup>. Reproduced wi STH efficiency of solar parental AWF system. (A) flustration of TF paveced AWF system<sup>10</sup>. Reproduced with permission of Ref.<br>
95, copyright Electic: (c) Schematic of pyroeletric as an external source for AWE system<sup>10</sup>. R 57, copyright Lissevarc, (c) Schematic di perolestion is an external source for AWE system." Reproduced with permission of Ref. 79, copyright Elsevier, (c) Schematic diagram of CRF-TENG wind energy harvester drives at fro on, copyright range and mother than the relativity wantered and model in the performance of the formulation of Ref. 97, copyright Elsevier. (g) Schematic illustration of self-powered AWE system using a water-flow-driven i TENG<sup>PP</sup>, Reproduced with permission of Ref. 98, copyright Wiley, (color on line)<br>TENGP<sup>PP</sup>, Reproduced with permission of Ref. 98, copyright Wiley, (color on line)<br>automnated preparation process to realize the con-<br>contro For the set of the surface of the surface of the surface of the set of the set of the reaction of Ref. 85, copyright Wiley. (c) Comparison of Ref. powered AWE system<sup>89</sup>. Reproduced with permission of Ref. ourse for AWE sy **Example 19 and an** experiment of Ref. 85, copyright Wiley. (c) Comparison of Ref. 85, copyright Wiley. (c) Comparison of Ref. ource for AWE system<sup>189</sup>. Reproduced with permission of Ref. cource for AWE system<sup>189</sup>. Repro CONTRIDUATION (CONTRIGUEST)<br>
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# Acknowledgements:

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# 碱性电解水高效制氢

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摘要: 与传统化石能源制氢技术相比, 利用可再生能源驱动电解水制氢技术具有绿色可持续和制氢效率高等优 势,被认为是目前最具前景的制氢方式。然而,由于电解水两极反应动力学缓慢、催化剂稳定性较差,限制 了其大规模发展。此外,阳极析氧反应存在较高的过电势, 从而导致当前制氢能耗与成本较高, 严重制约了 其商业化应用。为了解决上述问题与挑战, 本文对当前发展较为成熟的碱性电解水技术进行了综合讨论与分 析。首先, 对电解水发展历程中的重要节点进行了总结, 便于读者了解该领域。进一步, 从电催化剂、电 极、反应和系统的角度深入总结了提升电解水制氢性能的有效策略。作者分别介绍了近年来层状双金属氢氧 化物基电解水催化剂、电解水制氢耦合氧化反应以及可再生能源驱动的电解水系统的重要研究进展;同时对 结构化催化剂在电解水应用中的构效关系进行了深入分析。最后,对该领域存在的挑战和未来发展方向进行 了展望,希望能为氢能的发展和推广提供一定的思路。

关键词: 电解水; 制氢; 结构化电极; 耦合反应