Perspective

Progress and Opportunities for Exsolution in Electrochemistry

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Received: 14 February 2020; Accepted: 9 March 2020; Published: 11 March 2020

Abstract: This perspective gives the reader a broad overview of the progress that has been made in understanding the physics of the exsolution process and its exploitation in electrochemical devices in the last five years. On the basis of this progress, the community is encouraged to pursue unreported and under-reported opportunities for the advancement of exsolution in electrochemical applications through new materials discovery.

Keywords: solid-phase crystallization; solid oxide fuel cell (SOFC), solid-oxide electrolyzer cell (SOEC), energy conversion; in-situ particle growth

1. Introduction

Heterogeneous catalysts for energy conversion are most often supported catalysts, where a high surface-area support is decorated by catalytic nanoparticles.[1–3] While the support itself is not usually catalytically active, its crucial role in modulating the redox chemistry and stability of the active site has long been understood.[4–6] Furthermore, the support plays an important role in tailoring the local chemical environment surrounding the active site during catalysis through the adsorption of reactants and intermediates. For example, the support can be used to increase the concentration of desired adsorbed reactants in the proximity of the active site for more facile kinetics. Nanoparticles (or their soluble precursors) designed to provide active sites are generally synthesized independently of their support, and combined in a final synthetic step to generate the supported catalyst structure. The most common industrialized techniques to generate supported catalysts are “top-down” techniques such as incipient wetness impregnation, electro(less) deposition, and a variety of gas-phase deposition techniques (e.g., CVD, PVD). Such “top-down” techniques, in their essence, attempt to form the supported catalyst structure by decorating high surface-area supports with nanoparticles in a similar way to how one would decorate a cake. Unsurprisingly, this often leads to weak and superficial bonding between the metal and its support. [7–10] In both thermochemical and electrochemical catalytic processes, weak bonding at the interface between the nanoparticles and the support enables the nanoparticles to move, sinter, ripen, or even fall off. In the case of the electrodes meant to synthesize or consume carbon-based synthetic fuels, weak metal–support interactions (MSI) can enable carbon accumulation by the tip-growth mechanism, clogging pores and covering active sites, ultimately leading to the deactivation of the catalyst [11–14]. Given the importance of nanoparticle immobilization on the support by a strong MSI, the development of a widely applicable and single-step synthesis technique which could be used to improve catalyst durability is highly desirable [15].

In contrast to “top-down” techniques, the focus here is on an “inside-out” technique known as exsolution (also called solid-phase crystallization). Exsolution is a process where catalytic nanoparticles are instead grown by phase-separation in the solid phase within a mixed-metal oxide...
precursor. The bonds between metal cations and oxide anions within the lattice of the ceramic precursor can be broken in a reducing atmosphere at high temperature. Such a process reduces metal ions to their metallic state (or partially reduced state) in the form of nanoparticles. The resulting material is a supported catalyst where the reduced metal nanoparticles are dispersed about a support surface, or subsurface, as exemplified schematically in Figure 1. The support structure (or backbone) is the ceramic that is released when the desired metal ions have been removed from the lattice of the ceramic precursor material.

![Figure 1](image-url)  
**Figure 1.** Schematic representation of the exsolution process where exsolvable metals are present in their ionic state, typically residing on the B-site of the ceramic lattice. Upon exposure to a reducing atmosphere, exsolution occurs, and the exsolvable metals nucleate by reducing to their metallic state and decorate the surface of the released oxide support. Taken from [16] under CCBY license.

This perspective is meant to summarize some of the advancements that have been made in the last 5 years, including potential research paths moving forward. The interested reader is also directed to previous reviews on the exsolution phenomenon both within and outside the context of electrochemistry. [17–19]

2. Discussion

2.1 Recent Advancements in Exsolution Electrodes

One of the first reports of exsolution was produced in 2002 by auto manufacturers Daihatsu and Toyota in collaboration with the Japanese academy as a method for controlling automotive emissions.[20] In this study, the Pd particles used to treat exhaust gas could be cycled between their reduced state (metallic/exsolved) and their oxidized state (ionic/dissolved) by cycling the atmosphere between the reducing and oxidizing gases typically found in automotive exhaust. This would cycle Pd between its ionic state in the LaFe_{0.57}Co_{0.38}Pd_{0.05}O_{3} (LFCP) ceramic and its metallic state when Pd exsolves from giving Pd^{0}/LFC. This was found to be a clever strategy to mitigate the effects of nanoparticle agglomeration. When the Pd particles grew too large and negatively impacted catalysts, exposure to an oxidizing environment allowed the Pd particles to ingress/dissolve into the LFC backbone, forming the original LFCP phase. Afterwards, the LFCP could undergo exsolution anew and Pd would exsolve once more as small, highly dispersed, un-agglomerated nanoparticles.

While this initial application was not electrochemical in nature, the promise of extension to electrochemistry through the design of conductive ceramic backbones eventually followed, but did not pick up significant momentum until around 6–7 years ago. Additionally, electrochemical applications of the exsolution method still used the heated reducing gaseous environment as the driving force for exsolution. Exsolution electrodes have since been used in fuel-flexible solid-oxide fuel cells (SOFC’s), solid-oxide electrolyzer cells (SOEC), and cells which can switch functionality and polarization in order to store or produce energy as needed. The Irvine group showed in 2016 that the exsolution process could be driven electrochemically rather than thermochemically. Interestingly, the electrochemically-driven process occurred using a similar mechanism but on a timescale of seconds rather than minutes or hours. [21]
The exsolution process is similar, in many respects, to the precipitate hardening technique developed to modulate material properties via the growth of internal oxides. In contrast to precipitate hardening, where *internal* nucleation is desired to improve bulk material properties, most exsolution electrodes give rise to improved activity through the growth of nanoparticles on their *surface*. An important question which has received much attention is whether exsolution from oxide electrodes is a process which occurs on the surface, or one which begins subsurface, where the resulting internal nanoparticles are subsequently (or not) released to the free interface through strain fields. Experimental evidence using in-situ TEM [22], AFM [23], neutron diffraction [24], and the growth of symmetrical surface-bound core-shell particles’ [25], and theoretical studies [23,26,27] show that internal nucleation can occur and the particles’ release to the surface is driven by an asymmetric strain field described by the metal, surrounding oxide, and the free surface. Indeed, part of the reason that exsolved nanoparticles grown by exsolution exhibit a stronger MSI is attributed to the simultaneous formation of a socket within the precursor oxide and nucleation of the released particle. This is schematically depicted in Figure 2.

![Figure 2. Schematic of particle-socket formation during exsolution. (a) Nucleation; depicting the particle as partially embedded within the perovskite, (b) as the particle isotropically grows in the vertical and lateral directions, it pushes the perovskite lattice lifting it, (c) further growth of the particle leads to a volcano-shaped nanostructure, (d) the volcano shape interface relaxes and confinement is retained. Taken from [22] with permission.](image)

By contrast, many pictorial representations of the exsolution process show nucleation of reducible ions occurring only at the surface exposed to the reducing atmosphere. In this *external* representation, reducible ions diffuse upwards towards the surface and are reduced by the atmosphere. In principle, just as with the formation of oxides at high temperatures, both the internal and external growth mechanisms are plausible, and likely depend on the conditions of exsolution (i.e., temperature, time, and environment), the transport properties of the backbone, and the metal ion being exsolved. In the case of exsolution via heating the oxide in a hydrogen atmosphere, the competing processes are the inward diffusion of hydrogen into the ceramic against the outward diffusion of exsolvable ions to the surface. In the case where inward hydrogen diffusion dominates, internal growth may be expected. By contrast, where the outward diffusion of ions to the surface dominates, external growth may be expected. The diffusion of a high concentration of cations is also crucial for internal nucleation since the activity product \( (\text{M}^{x+} \cdot \text{O}_2^-) \) must pass a certain threshold for internal nucleation.[28] This product can be modulated by the placement of vacancies in the cation sublattice though the synthesis of A-site-deficient starting materials or by changing the fraction of exsolvable metal in the precursor. Indeed, many studies have shown that exsolution is more favorable from A-site deficient perovskites.[16,29–31] Therefore, low-cation transport properties and lower oxygen partial pressures \( (p_{O_2}) \) should favor internal nucleation. This concept was recently expanded upon by exsolving particles both on the surface and in the subsurface layers in \( \text{La}_{0.8}\text{Ce}_{0.1}\text{Ni}_{0.4}\text{Ti}_{0.6}\text{Ni}_{0.4}\text{O}_3 \), thus reciprocally straining the subsurface particles with the perovskite and significantly enhancing oxygen exchange.[32] While the application of this later discovery was not electrochemical in nature, the concept of enhanced oxygen mobility via subsurface growth may have
applications in electrochemical oxygen reduction electrodes. Furthermore, the size and number density of particles exsolved from a given backbone can be modulated by changing the doping level, time of exsolution, or temperature of exsolution.

At first, the use of exsolution as a technique to design simultaneously stable and active electrodes for SOFCs was only an academic endeavor. Electrodes fashioned by exsolution originally provided additional stability, but at the expense of activity and conductivity. Indeed, exsolution anodes gave a significantly worse performance compared to the standard NiO/YSZ cermet and were thus not considered as an industrially viable replacement. Recently, Barnett has shown that exsolution electrodes on the basis of A-site-deficient and B-site-doped strontium titanates have comparable current densities to NiO/YSZ, and are therefore becoming industrially relevant materials.[33] Figure 3 shows that Sr$_{0.95}$Ti$_{0.3}$Fe$_{0.63}$Ni$_{0.07}$O$_{3-\delta}$ (STFN)-based anodes under a flow of humid hydrogen could generate over 4 A/cm$^2$, making them highly competitive with (if not exceeding) the performance of NiO cermets [33,34]

![Figure 3](image.png)

Figure 3. Current–Voltage–Power curves for SrTi$_{0.3}$Fe$_{0.7}$O$_{3-\delta}$ (STF) and Sr$_{0.95}$Ti$_{0.3}$Fe$_{0.63}$Ni$_{0.07}$O$_{3-\delta}$ (STFN) anode cells under humidified H$_2$ conditions with a fuel flow of 100 sccm (A–B) at different temperatures and (C–D) hydrogen partial pressures. Taken from [33] with permission.

These results show great promise that cleverly engineered stoichiometry can be synthesized in order to form mixed ionic–electric conductors (MIECs), tailor the electronic properties of the exsolved catalytic nanoparticles through alloying, [33,35–39] and utilize strain engineering or twinning to enhance catalytic properties.[40] One of the major advantages of SOFCs over room temperature (e.g., PEM) fuel cells is their fuel flexibility and ability to operate using non-precious-metal catalysts. Under conditions where carbonaceous feeds are used, carbon accumulation (coking) can impede the longevity of the device, making it industrially irrelevant. Exsolution catalysts have been thoroughly studied under a variety of methane oxidation conditions which are susceptible to coking.[37,41–45] It was found that the strong MSI imbued by the socketed configuration between the metal and the support was able to mechanically block the tip-growth mechanism by which multi-walled carbon nanotubes (MWCNTs) grow. This discrete advantage from thermochemical methane-reforming appears to be completely transferable to the design of SOFC anodes which operate on carbonaceous gas feeds such as CH$_4$ and CO.[31,46,47]

Exsolution has also been used recently to drive electrolysis cells for H$_2$O and CO$_2$. Many of the design concepts described above have been exploited to design exsolution electrodes for SOEC CO$_2$-
electrolysis. For example, the intentional introduction of A-site deficiencies which showed promising results in the exsolution of cobalt from a (Pr,Ba)₂Mn₂₋₃FeₓO₅₋₃ backbone,[48] was shown to be reversible on a Ruddlesden–Popper backbone and efficient at CO₂ conversion to CO.[49] Additionally, bimetallic FeNi₃ nanoparticles were shown as an effective catalysts exsolved from the stoichiometric double perovskite SrFe₁₋₃MnₓO₅₋₃.[50] Ultimately, CO₂ electrolysis cells using exsolution electrodes show particular promise because the current densities achieved are beginning to match those found in SOFC devices (>2.5 mA/cm²).[51] An impressive application for exsolution electrodes is for the co-generation of valuable chemical products (CH₄, CO, H₂) and electricity. Ru exsolution from La₀.₄₃Ca₀.₃₇Rh₀.₀₆Ti₀.₉₄O₃ was shown to be effective at co-electrolysis (where CO₂ and H₂O are reduced to CO and H₂ at the cathode), CH₄-assisted co-electrolysis (where CH₄ is simultaneously oxidized to CO₂ and H₂O at the anode via O₂⁻ transport) and co-generation, where the reversible potential becomes negative and electricity and chemical products are produced together.[52] In addition to the examples cited above, a partial summary of the advancements made in the design of exsolution electrodes is given in Table 1.

### Table 1. Partial list of advancements in exsolution electrode design from last 5 years.

| Material | System | Notes | Year | Ref |
|----------|--------|-------|------|-----|
| Pr₀.₆₅Ba₀.₃₅Mn₀.₉₇₅Ni₀.₀₂₅O₃ | H₂ SOFC | In-situ neutron diffraction of Ni exsolution process | 2020 | [53] |
| CaTi₀.₉₄Ni₀.₀₆O₃₋₅ | Oxygen reduction | A-site exsolution | 2020 | [54] |
| Sr₀.₉₅(Ti₀.₃Fe₀.₆₃Ni₀.₀₇)O₃₋₅ | H₂ SOFC | Effect of non-stoichiometry in Sr(Ti,Fe,Ni)O₃ | 2019 | [34] |
| (Pr,Ba)₂Mn₂₋₃Fe₀.₅O₅₋₃ | CO₂ SOEC | Exsolution of Fe/MnOₓ for CO₂ reduction | 2019 | [48] |
| Sr₂CoMo₀.₉₅Fe₀.₅O₆₋₅ | H₂/CH₄ SOFC | Twinning in Co-Fe exsolution | 2019 | [40] |
| Sr₂Fe₁₋₀.₉₅Ni₀.₀₅O₆₋₅ | H₂ SOFC | Thermal stability of Ni exsolution | 2019 | [55] |
| Sr₂Fe₁₋₀.₉₅Ni₀.₀₅O₆₋₅ | H₂ SOFC | Co exsolution from double-perovskites | 2019 | [56] |
| SrV₀.₅Mo₀.₅Ni₀.₅O₆₋₅ | H₂ SOFC | B-site excess doping | 2019 | [57] |
| La₁₋₀.₅Sr₁₋₀.₅Mn₀.₅Ni₀.₅O₇₋₅ | H₂ SOFC | Exsolution in Ruddlesden Popper Phases | 2019 | [46] |
| SrTi₀.₇₅Co₀.₂₅O₄₋₅ | CO oxidation | Particle density and growth kinetics | 2019 | [58] |
| La₀.₉₅Sr₁₋₀.₅Mn₀.₅Ni₀.₅O₆₋₅ | H₂ SOFC | Reversible Fe exsolution | 2019 | [59] |
| La₀.₉₅Sr₀.₅Co₀.₄Mn₀.₅O₃ | CO₂ SOEC | Exsolution in Ruddlesden Popper Phases | 2019 | [49] |
| La₀.₈₅Ca₀.₁₇Nio.₀₆Tio.₉₄O₃ | Fundamental | In-situ TEM of Ni exsolution | 2019 | [22] |
| LaFePd₀.₁₅O₃₋₅ | CO sensor | Pd exsolution | 2019 | [60] |
| AgNbO₃ | NH₃ sensor | Ag exsolution | 2019 | [61] |
| SrGdNi₀.₅Mn₀.₅O₄₋₅ | H₂ SOFC | Improved redox stability | 2019 | [62] |
| La₀.₈₅(Ca₀.₇Nio.₀₃Tio.₉₄O₃) | Fundamental | Strain enhanced exsolution | 2019 | [63] |
| Sr₀.₉₅(Ti₀.₃Fe₀.₆₃Ni₀.₀₇)O₃ | H₂ SOFC | High current density | 2018 | [33] |
| La₀.₈₅Ca₀.₁₇Ni₀.₅Nb₀.₅O₄ | H₂ SOFC | Enhanced proton conductivity | 2018 | [64] |
| (Gd₀.₂₅Ni₀.₇₅Co₀.₅O₂₋₅ | H₂ SOFC | Exsolution in Gd doped perovskites | 2018 | [65] |
| SrTiWO₃ | H₂ Production | Exsolution in photocatalysis | 2018 | [66] |
| Rh/3DOM LaNi₀.₉₅Al₀.₀₅O₃ | CO₂ reduction | Rh-Ni exsolution for methanation | 2018 | [67] |
| Many | Co oxidation | Predetermined location | 2018 | [68] |
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| Material                  | Role of extended defects              | Year | Reference |
|---------------------------|---------------------------------------|------|-----------|
| LaNiO₃                    | Fundamental                           | 2017 | [43]      |
| Pr₀.₅Ba₀.₅Mn₀.₈₅T₀.₁₅O₃₋δ | H₂ SOFC Exsolution in layered perovskites | 2017 | [69]      |
| Sr₀.₉₅Ag₀.₀₅Nb₀.₁Co₀.₉O₃₋δ | LT-SOFC Oxygen reduction at low temperature | 2016 | [70]      |
| Co-doped Pr₀.₃Ba₀.₇MnO₃  | SOFC/SOEC High population, dual use   | 2016 | [71]      |

2.2. Future Research Directions

Despite recent advancements in the design of exsolution electrodes for electrochemical applications, many research opportunities remain in order to broaden the implementation of the exsolution technique and to widen the breadth of materials from which exsolution is studied. A brief list of such opportunities is listed below.

2.2.1. Exsolution from Heteroanionic Ceramics

As is evident from the previous sections, a significant amount of momentum has been established in understanding the role of cationic substitutions on the physics of exsolution and their subsequent material and catalytic properties. Despite this breadth, there remains no robust experimental research detailing the effect of substitutions in the anion sublattice on exsolution electrodes. For example, the typical oxygen-filled anion sublattice can be partially (or completely) substituted by other anions, such as nitrogen (N), sulfur (S), chlorine (Cl), or fluorine (F). Each of these anions has a different radius, electronegativity, and charge (N, F, Cl) compared to oxygen, the effects of which have not been explored on exsolution. In general, research on heteroanionic materials (HAM) by comparison to their oxide counterparts is in its infancy, and studying the physics and applications of exsolution from HAMs could end up bringing about an entirely new class of catalytic materials. In some cases, partial heteroanionic substitution is possible for a wide range of materials. Oxygen and nitrogen show many chemical and structural similarities, such as coordination numbers and ionic radii. Consequently, they can sometimes be substituted for each other to form oxynitrides. In addition to the perovskite structure, oxynitrides have been reported in the spinel, Ruddlesden–Popper, pyrochlore, baddeleyite, sheelite, and apatite structures.[72] Despite the many similarities between the oxygen and nitrogen anion, they differ in electronegativity and polarizability, giving rise to changes in bond strength and degree of covalency within the material as substitutions are made.[73] Investigation into how these differences impact the exsolution process and the resultant materials’ properties is therefore an exciting, unexplored field of research. Such materials could be used as photocatalysts or anode materials for ammonia oxidation (in the case of exsolution from perovskite oxynitrides). Of equal importance would be to study the ingress kinetics of the exsolved particles into the heteroanionic backbone. Possibilities include fully oxidizing the ceramic and then introducing the heteroanion in a second recovery step, or to attempt to control the ingress of oxynitrides or oxysulfides by carefully controlling the equilibrium with NO₃ or SO₃, respectively.

2.2.2. Exsolution in Photocatalysis

With the advancement in understanding of electrochemically-driven exsolution, there remains the possibility that exsolution can be driven photo-catalytically in photoactive ceramics with sufficiently low bandgaps or significantly high thermal stability. It remains of interest to determine how the localized phenomenon of charge separation influences the location and kinetics of exsolution, and how the exsolution process itself impacts the bandgap, absorbance, and photocatalytic properties of such materials. Even in the event that the exsolution process is thermally driven, there remains a gap in understanding whether such exsolution electrodes can be tailored for photocatalytic application. Exsolution in photocatalysis was recently reported using tungsten-doped strontium titanate.[66]

2.2.3. Predetermined Location of Exsolution
Several studies have shown that the exsolution of particles occurred preferentially at 2D defects such as grain boundaries\cite{58,68,74,75} and Ruddlesden–Popper stacking faults\cite{43,76}. In-situ TEM has shown that such defects serve as nucleation sites and, consequently, nuclei can be found to form in these locations at lower temperatures compared to the defect-free regions of the same material.\cite{43} This phenomenon can be exploited to design materials (not necessarily for catalytic purposes) where the nanoparticles can be grown at these predetermined locations. In some cases, these particles could ingress into the host material upon exposure to higher pO$_2$, enabling the reversible growth of nanoparticles in at these locations.

2.2.4. Exsolved Core-shell and Core-skin Particles

One of the key disadvantages of the exsolution technique is the lack of structural variety that it affords. While the stability and ease of this technique represent clear advantages, diversity in active-site engineering is a critical aspect of catalysis. Any technique that cannot be used broadly to vary the structure of the active site is at a discrete disadvantage compared to other synthetic techniques. To date, a vast majority of papers on exsolution focus on single-metal or alloy particles where atoms are homogeneously distributed. This puts the exsolution technique at a marked disadvantage compared to other techniques where diverse and complex structures such as core-shell, core-skin, single-atom, nano-rafts, and Janus particles can be synthesized according to the needs of a specific reaction or system. There are currently sparse studies which have found the core-shell structure of a metal and its native oxide,\cite{77} and with metals and an oxide from another metal.\cite{25,78} The study of exsolvable core-shell and core-skin nanoparticles is therefore of significant interest as it can increase the structural diversity and ability to tailor electrodes fashioned by exsolution. A previously employed technique was the use of two metals with significantly different reducibility and transport properties. An additional potential technique to form core-skin particles may be the exsolution of a alloy particle where the two metals have a large segregation energy.\cite{79}

2.2.5. Exsolution from Thin Films Cast on High Surface Area Supports

One of the other marked disadvantages of exsolution from perovskite-family materials is their relatively low surface area. It is therefore of considerable interest to exploit the exsolution mechanism in a configuration which would allow a support with a specific surface area of hundreds of meters squared per gram rather than tens. This field has already seen some advancement by casting a Pt-doped CaTiO$_3$ onto high-surface-area MgAl$_2$O$_4$.\cite{80} This technique exploits the physics of exsolution within a thin film coated on a high surface-area support. Since ingress and exsolution kinetics are relatively slow, the use of thin films is also advantageous in order to minimize diffusion distances.\cite{81} Additionally, thin films have been used to engineer the lattice strain experienced by materials during exsolution by varying the misfit strain using different substrates.\cite{63}

2.2.6. Exsolution Electrodes for Ambient Temperature Applications

Although most all ceramic backbones (save SrRuO$_3$) are incapable of sufficient electrical conductivity at room temperature, the use of exsolution electrodes for room temperature applications should not be ignored. Jian et al.\cite{82} recently showed that the exsolution of Co from La$_{0.9}$Fe$_{0.9}$Co$_{0.1}$O$_3$ (LFCO) could be used at room temperature if mixed with a conductive carbon black ink. This composite electrode showed enhancement for both oxygen evolution and oxygen reduction reactions. Although electrical conductivity is facilitated via the exterior of the particle rather than through its bulk (here lanthanum ferrite), the stabilization, strain, and alloying strategies mentioned above can still be actualized. As a large number of room temperature electrochemical reactions still suffer from longevity and durability issues, exploring this strategy is highly desirable.

3. Conclusions
In the last five years, exsolution electrodes have transitioned from a field of academic inquiry to that of industrial promise. SOFC electrodes fashioned by exsolution can now match or exceed the current density of their NiO cermet counterparts and may not suffer the same chemical and mechanical stability constraints. Furthermore, the use of exsolution electrodes in electrolytic or switchable cells shows great promise, as the current densities achieved by steam or CO₂ reduction are of a similar magnitude to fuel cell operation. The mechanisms of exsolution, particularly of Ni, have been well studied, and the process has been observed by electron microscopy, diffraction, and atom probe techniques in order to better understand the source of the improved metal support interaction (MSI) imbued by exsolution. Novel materials designed by exsolution could show great promise to expand the breadth of applications for which exsolved electrodes are used.

**Funding:** The author thanks the Israeli Ministry of Energy grants 215-11-033, 217-11-027, and 218-11-023 for supporting projects related to nanoparticle exsolution for energy storage and conversion.

**Conflict of interest:** The author declares no conflict of interest.

**References**

1. Meille, V. Review on methods to deposit catalysts on structured surfaces. *Appl. Catal. A Gen.* 2006, 315, 1–17.
2. Prieto, G.; Zečević, J.; Friedrich, H.; de Jong, K.P.; de Jongh, P.E. Towards stable catalysts by controlling collective properties of supported metal nanoparticles. *Nat. Mater.* 2013, 12, 34–39.
3. Munnik, P.; de Jongh, P.E.; de Jong, K.P. Recent developments in the synthesis of supported catalysts. *Chem. Rev.* 2015, 115, 6687–6718.
4. Nakamura, J.; Aikawa, K.; Sato, K.; Uchijima, T. Role of support in reforming of CH₄ with CO₂ over Rh catalysts. *Catal. Lett.* 1994, 25, 265–270.
5. Schubert, M.M.; Hackenberg, S.; van Veen, A.C.; Muhler, M.; Plzak, V.; Behm, R.J. CO oxidation over supported gold catalysts—“Inert” and “active” support materials and their role for the oxygen supply during reaction. *J. Catal.* 2001, 197, 113–122.
6. Micoud, F.; Maillard, F.; Bonnefont, A.; Job, N.; Chatenet, M. The role of the support in CO ads monolayer electrooxidation on Pt nanoparticles: Pt/WOₓ vs. Pt/C. *Phys. Chem. Chem. Phys.* 2010, 12, 1182–1193.
7. Neagu, D.; Oh, T.-S.; Miller, D.N.; Ménard, H.; Bukhari, S.M.; Gamble, S.R.; Gorte, R.J.; Vohs, J.M.; Irvine, J.T. Nano-socketed nickel particles with enhanced coking resistance grown in situ by redox exsolution. *Nat. Commun.* 2015, 6, 8120.
8. Ratkovic, S.; Vujicic, D.; Kiss, E.; Boskovic, G.; Geszti, O. Different degrees of weak metal–support interaction in Fe–(Ni)/Al₂O₃ catalyst governing activity and selectivity in carbon nanotubes’ production using ethylene. *Mater. Chem. Phys.* 2011, 129, 398–405.
9. Park, C.; Keane, M.A. Catalyst support effects in the growth of structured carbon from the decomposition of ethylene over nickel. *J. Catal.* 2004, 221, 386–399.
10. Rosen, B.A.; Singh, S. Fossil Fuels: Coke-Resistant Nanomaterials for Gas-to-Liquid (GTL) Fuels. *Nanotechnol. Energy Sustain.* 2017, 59–82, doi:10.1002/9783527696109.ch3.
11. Pakhare, D.; Spivey, J. A review of dry (CO 2) reforming of methane over noble metal catalysts. *Chem. Soc. Rev.* 2014, 43, 7813–7837.
12. Sutthiumporn, K.; Maneerung, T.; Kathiraser, Y.; Kawi, S. CO₂ dry-reforming of methane over La₀.₈Sr₀.₂Ni₀.₈M₀.₂O₃ perovskites (M = Bi, Co, Cr, Cu, Fe): Roles of lattice oxygen on C–H activation and carbon suppression. *Int. J. Hydrog. Energy* 2012, 37, 11195–11207.
13. Arandiyan, H.; Li, J.; Ma, L.; Hashemnejad, S.M.; Mirzaei, M.Z.; Chen, J.; Chang, H.; Liu, C.; Wang, C.; Chen, L. Methane reforming to syngas over LaNiₓFe₁₋ₓO₃ (0 ≤ x ≤ 1) mixed-oxide perovskites in the presence of CO₂ and O₂. *J. Ind. Eng. Chem.* 2012, 18, 2103–2114.
14. Gallego, G.S.; Batiot-Dupeyrat, C.; Barrault, J.; Florez, E.; Mondragon, F. Dry reforming of methane over LaNi₁₋yByO₃ ± δ (B = Mg, Co) perovskites used as catalyst precursor. *Appl. Catal. A Gen.* 2008, 334, 251–258.
15. Tsai, C.; Abild-Pedersen, F.; Nørskov, J.K. Tuning the MoS₂ edge-site activity for hydrogen evolution via support interactions. *Nano Lett.* 2014, 14, 1381–1387.
16. Neagu, D.; Tsekouras, G.; Miller, D.N.; Ménard, H.; Irvine, J.T.S. In situ growth of nanoparticles through control of non-stoichiometry. *Nat. Chem.* **2013**, *3*, 916–923.

17. Huang, K. An emerging platform for electrocatalysis: Perovskite exsolution. *Sci. Bull.* **2016**, *61*, 1783–1784.

18. Kan, W.H.; Samson, A.J.; Thangadurai, V. Trends in electrode development for next generation solid oxide fuel cells. *J. Mater. Chem. A* **2016**, *4*, 17913–17932.

19. Irvine, J.T.S.; Neagu, D.; Verbraeken, M.C.; Chatzichristodoulou, C.; Graves, C.; Mogensen, M.B. Evolution of the electrochemical interface in high-temperature fuel cells and electrolyzers. *Nat. Energy* **2016**, *1*, 15014.

20. Nishihata, Y.; Mizuki, J.; Akao, T.; Tanaka, H.; Uenishi, M.; Kimura, M.; Okamoto, T.; Hamada, N. Self-regeneration of a Pd-perovskite catalyst for automotive emissions control. *Nature* **2020**, *510*, 164–167.

21. Myung, J.-H.; Neagu, D.; Miller, D.N.; Irvine, J.T.S. Switching on electrocatalytic activity in solid oxide cells. *Nature* **2016**, *537*, 528–531.

22. Neagu, D.; Kyriakou, V.; Roiban, I.-L.; Aouine, M.; Tang, C.; Caravaca, A.; Kousi, K.; Schreur-Piet, I.; Metcalfe, I.S.; Vernoux, P.; et al. In situ Observation of Nanoparticle Exsolution from Perovskite Oxides: From Atomic Scale Mechanistic Insight to Nanoscale Tailoring. *ACS Nano* **2019**, *13*, 12996–13005.

23. Oh, T.-S.; Rahani, E.K.; Neagu, D.; Irvine, J.T.S.; Shenoy, V.B.; Gorte, R.J.; Voht, J.M. Evidence and Model for Strain-Driven Release of Metal Nanocatalysts from Perovskites during Exsolution. *J. Phys. Chem. Lett.* **2015**, *6*, 5106–5110.

24. Haag, J.M.; Barnett, S.A.; Richardson, J.W.; Poeppelmeier, K.R. Structural and Chemical Evolution of the SOFC Anode La$_{0.30}$Sr$_{0.70}$Fe$_{0.70}$Cr$_{0.30}$O$_3$ upon Reduction and Oxidation: An in Situ Neutron Diffraction Study. *Chem. Mater.* **2010**, *22*, 3283–3289.

25. Buhanon, M.; Singh, S.; Komarala, E.P.; Rosen, B.A. Expanding possibilities for solid-phase crystallization by exsolving tunable Pd–NiO core–shell nanostructures. *CrystEngComm* **2018**, *20*, 6372–6376.

26. Bergamaschini, R.; Rosen, B.A.; Montalenti, F.; Colin, J. Motion of crystalline inclusions by interface diffusion in the proximity of free surfaces. *J. Nanopart. Res.* **2019**, *21*, 271.

27. Gao, Y.; Lu, Z.; You, T.L.; Wang, J.; Xie, L.; He, J.; Ciucci, F. Energetics of Nanoparticle Exsolution from Perovskite Oxides. *J. Phys. Chem. Lett.* **2018**, *9*, 3772–3778.

28. Birks, N.; Meier, G.H.; Pettit, F.S. *Introduction to the High Temperature Oxidation of Metals*; Cambridge University Press: Cambridge, UK, 2006.

29. Sun, Y.; Li, J.; Zeng, Y.; Amirkhiz, B.S.; Wang, M.; Behnamian, Y.; Luo, J. A-site deficient perovskite: The parent for in situ exsolution of highly active, regenerable nano-particles as SOFC anodes. *J. Mater. Chem. A* **2015**, *3*, 11048–11056.

30. Sun, Y.-F.; Li, J.-H.; Wang, M.-N.; Hua, B.; Li, J.; Luo, J.-L. A-site deficient chromite perovskite with in situ exsolution of nano-Fe: A promising bi-functional catalyst bridging the growth of CNTs and SOFCs. *J. Mater. Chem. A* **2015**, *3*, 14625–14630.

31. Sun, Y.-F.; Li, J.-H.; Cui, L.; Hua, B.; Cui, S.-H.; Li, J.; Luo, J.-L. A-site-deficiency facilitated in situ growth of bimetallic Ni–Fe nano-alloys: A novel coking-tolerant fuel cell anode catalyst. *Nanoscale* **2015**, *7*, 11173–11181.

32. Kousi, K.; Neagu, D.; Bekris, L.; Papaioannou, E.I.; Metcalfe, I.S. Endogenous Nanoparticles Strain Perovskite Host Lattice Providing Oxygen Capacity and Driving Oxygen Exchange and CH$_4$ Conversion to Syngas. *Angew. Chem. Int. Ed.* **2019**, doi:10.1002/anie.201915140.

33. Zhu, T.; Troiani, H.E.; Mogi, L.V.; Han, M.; Barnett, S.A. Ni-Substituted Sr(Ti,Fe)O$_3$ SOFC Anodes: Achieving High Performance via Metal Alloy Nanoparticle Exsolution. *Joule* **2018**, *2*, 478–496.

34. Zhu, T.; Troiani, H.; Mogi, L.V.; Sanyata, M.; Han, M.; Barnett, S.A. Exsolution and electrochemistry in perovskite solid oxide fuel cells anodes: Role of stoichiometry in Sr(Ti,Fe,Ni)O$_3$. *J. Power Sources* **2019**, *439*, 227077.

35. Kwon, O.; Kim, K.; Joo, S.; Jeong, H.Y.; Shin, J.; Han, J.W.; Sengodan, S.; Kim, G. Self-assembled alloy nanoparticles in a layered double perovskite as a fuel oxidation catalyst for solid oxide fuel cells. *J. Mater. Chem. A* **2018**, *6*, 15947–15953.

36. Chen, X.; Ni, W.; Wang, J.; Zhong, Q.; Han, M.; Zhu, T. Exploration of Co-Fe alloy precipitation and electrochemical behavior hysteresis using Lanthanum and Cobalt co-substituted SrFeO$_3$-δ SOFC anode. *Electrochim. Acta* **2018**, *277*, 226–234.

37. Zubenko, D.; Singh, S.; Rosen, B.A. Exsolution of Re-alloy catalysts with enhanced stability for methane dry reforming. *Appl. Catal. B Environ.* **2017**, *209*, 711–719.
38. Li, M.; Hua, B.; Zeng, Y.; Amirkhiz, B.S.; Luo, J.-L. Thermally stable and coking resistant CoMo alloy-based catalysts as fuel electrodes for solid oxide electrochemical cells. J. Mater. Chem. A 2018, 6, 15377–15385.

39. Fowler, D.E.; Messner, A.C.; Miller, E.C.; Slone, B.W.; Barnett, S.A.; Poeppelmeier, K.R. Decreasing the Polarization Resistance of (La, Sr)CrO₃–δ Solid Oxide Fuel Cell Anodes by Combined Fe and Ru Substitution. Chem. Mater. 2015, 27, 3683–3693.

40. Zhang, W.; Wang, H.; Guan, K.; Meng, J.; Wei, Z.; Liu, X.; Meng, J. Enhanced Anode Performance and Coking Resistance by In Situ Exsolved Multiple-Twinned Co–Fe Nanoparticles for Solid Oxide Fuel Cells. ACS Appl. Mater. Interfaces doi.org/10.1021/acsami.9b14655.

41. Wang, L.; Hu, R.; Liu, H.; Wei, Q.; Gong, D.; Mo, L.; Tao, H.; Zhang, Z. Encapsulated Ni@La₂O₃/SiO₂ Catalyst with a One-Pot Method for the Dry Reforming of Methane. Catalysts 2019, 10, 38.

42. Papargyriou, D.; Miller, D.N.; Irvine, J.T.S. Exsolution of Fe–Ni alloy nanoparticles from (La, Sr)(Cr, Fe, Ni)O₃ perovskites as potential oxygen transport membrane catalysts for methane reforming. J. Mater. Chem. A 2019, 7, 15812–15822.

43. Singh, S.; Prestat, E.; Huang, L.-F.; Rondinelli, J.M.; Haigh, S.J.; Rosen, B.A. Role of 2D and 3D defects on the reduction of LaNiO₃ nanoparticles for catalysis. Sci. Rep. 2017, 7, 10080.

44. Wei, T.; Jia, L.; Luo, J.-L.; Chi, B.; Pu, J.; Li, J. CO₂ dry reforming of CH₄ with Sr and Ni co-doped LaCrO₃ perovskite catalysts. Appl. Surf. Sci. 2020, 506, 144699.

45. Oh, J.H.; Kwon, B.W.; Cho, J.; Lee, C.H.; Kim, M.K.; Choi, S.H.; Yoon, S.P.; Han, J.; Nam, S.W.; Kim, J.Y.; Jang, S.S.; Lee, K.B.; Ham, H.C. Importance of Exsolution in Transition-Metal (Co, Rh, and Ir)-Doped LaCrO₃ Perovskite Catalysts for Boosting Dry Reforming of CH₄ Using CO₂ for Hydrogen Production. Ind. Eng. Chem. Res. 2019, 58, 6385–6393.

46. Vecino-Martillana, S.; Gauthier-Maradei, P.; Huvé, M.; Serra, J.M.; Roussel, P.; Gauthier, G.H. Nickel Exsolution-Driven Phase Transformation from an n = 2 to an n = 1 Ruddlesden-Popper Manganite for Methane Steam Reforming Reaction in SOFC Conditions. ChemCatChem 2019, 11, 4631–4641.

47. Atkinson, A.; Barnett, S.; Gorte, R.J.; Irvine, J.T.S.; McEvoy, A.J.; Mogensen, M.; Singhal, S.C.; Vohs, J. Advanced anodes for high-temperature fuel cells. In Materials for Sustainable Energy; Co-Published with Macmillan Publishers Ltd.: London, UK, 2010; pp. 213–223.

48. Zhu, J.; Zhang, W.; Li, Y.; Yue, W.; Geng, G.; Yu, B. Enhancing CO₂ catalytic activation and direct electroreduction on in-situ exsolved Fe/MnOₓ nanoparticles from (Pr, Ba)₂Mn₂-yFeₙO₅ + δ Ruddlesden-Popper Material as highly active catalyst for CO₂ electrolysis to CO. Appl. Catal. B Environ. 2019, 248, 147–156.

49. Lv, H.; Lin, L.; Zhang, X.; Gao, D.; Song, Y.; Zhou, Y.; Liu, Q.; Wang, G.; Bao, X. In situ exsolved FeNi₃ nanoparticles on nickel doped Sr₂Fe₁.5Mo₀.5O₆–δ perovskite for efficient electrochemical CO₂ reduction reaction. J. Mater. Chem. A 2019, 7, 11967–11975.

50. Liu, S.; Liu, Q.; Luo, J.-L. Highly Stable and Efficient Catalyst with In Situ Exsolved Fe–Ni Alloy Nanospheres Socketed on an Oxygen Deficient Perovskite for Direct CO₂ Electrolysis. ACS Catal. 2016, 6, 6219–6228.

51. Kyriakou, V.; Neagu, D.; Zafeiropoulos, G.; Sharma, R.K.; Tang, C.; Kousi, K.; Metcalfe, I.S.; van de Sanden, M.C.M.; Tsampas, M.N. Symmetrical Exsolution of Rh Nanoparticles in Solid Oxide Cells for Efficient Syngas Production from Greenhouse Gases. ACS Catal. 2019, 1278–1288. doi:10.1021/acscatal.9b04424.

52. Bahout, M.; Managutti, P.; Dorcet, V.; la Salle, A.L.G.; Paofai, S.; Hansen, T.C. In situ exsolution of Ni particles on the PrBaMnO₃ SOFC electrode material monitored by high temperature neutron powder diffraction under hydrogen. J. Mater. Chem. A 2020, 8, 3590–3597.

53. Lee, J.G.; Myung, J.-H.; Naden, A.B.; Jeon, O.S.; Shul, Y.G.; Irvine, J.T.S. Replacement of Ca by Ni in a Perovskite Titanate to Yield a Novel Perovskite Exsolution Architecture for Oxygen-Evolution Reactions. Adv. Energy Mater. 2020, 1903693. doi:10.1002/aenm.201903693.

54. Zhang, T.; Zhao, Y.; Zhang, X.; Zhang, H.; Yu, N.; Liu, T.; Wang, Y. Thermal Stability of an in Situ Exsolved Metallic Nanoparticle Structured Perovskite Type Hydrogen Electrode for Solid Oxide Cells. ACS Sustain. Chem. Eng. 2019, 7, 17834–17844.
56. Yang, Y.; Wang, Y.; Yang, Z.; Lei, Z.; Jin, C.; Liu, Y.; Wang, Y.; Peng, S. Co-substituted SrFe1-xMoxO4-δ as anode materials for solid oxide fuel cells: Achieving high performance via nanoparticle exsolution. *J. Power Sources* 2019, 438, 226989.

57. Wan, Y.; Xing, Y.; Xie, Y.; Shi, N.; Xu, J.; Xia, C. Vanadium-Doped Strontium Molybdate with Exsolved Ni Nanoparticles as Anode Material for Solid Oxide Fuel Cells. *ACS Appl. Mater. Interfaces* 2019, 11, 42271–42279.

58. Jo, Y.-R.; Koo, B.; Seo, M.-J.; Kim, J.K.; Lee, S.; Kim, K.; Han, J.W.; Jung, W.; Kim, B.-J. Growth Kinetics of Individual Co Particles Ex-solved on SrTl0.75Co0.25O3 Polycrystalline Perovskite Thin Films. *J. Am. Chem. Soc.* 2019, 141, 6690–6697.

59. Qi, H.; Yang, T.; Li, W.; Ma, L.; Hu, S.; Shi, W.; Sabolsky, E.M.; Zondlo, J.W.; Hart, R.; Hackett, G.A.; Liu, X. Reversible In-Situ Exsolution of Fe Catalyst in La0.5Sr1.5Fe1.5Mo0.5O6-δ Anode for SOFCs. *ECS Trans.* 2019, 91, 1701–1710.

60. Li, X.; Dai, L.; He, Z.; Meng, W.; Li, Y.; Wang, L. In situ exsolution of PdO nanoparticles from non-stoichiometric LaFePd0.95Ox+δ electrode for impedancemetric NO2 sensor. *Sens. Actuators B Chem.* 2019, 298, 126827.

61. Li, X.; Dai, L.; He, Z.; Meng, W.; Li, Y.; Wang, L. Enhancing NH3 sensing performance of mixed potential type sensors by chemical exsolution of Ag nanoparticles on AgNbO3 sensing electrode. *Sens. Actuators B Chem.* 2019, 298, 126854.

62. Kim, K.J.; Rath, M.K.; Kwak, H.H.; Kim, H.J.; Han, J.W.; Hong, S.-T.; Lee, K.T. A Highly Active and Redox-Stable SrGdNi0.2Mn0.8O4±δ Anode with in Situ Exsolution of Nanocatalysts. *ACS Catal.* 2019, 9, 1172–1182.

63. Han, H.; Park, J.; Nam, S.Y.; Kim, K.J.; Choi, G.M.; Parkin, S.S.P.; Jang, H.M.; Irvine, J.T.S. Lattice strain-enhanced exsolution of nanoparticles in thin films. *Nat. Commun.* 2019, 10, 1471.

64. Li, M.; Hong, T.; Cheng, J.; Chen, Z.; Xu, C. Enhanced proton conductivity of La0.5Sr0.5Ni0.2Mn0.8-xO3 (0.01 ≤ x ≤ 0.3) through in-situ exsolution of metallic nanocatalysts. *Mater. Chem. Phys.* 2018, 208, 226–236.

65. Tan, J.; Lee, D.; Ahn, J.; Kim, B.; Moon, J. Thermally driven in situ exsolution of Ni nanoparticles from (Ni, Gd)CeO2 for high-performance solid oxide fuel cells. *J. Mater. Chem. A* 2018, 6, 18133–18142.

66. Sun, Y.-F.; Yang, Y.-L.; Chen, J.; Li, M.; Zhang, Y.-Q.; Li, J.-H.; Hua, B.; Luo, J.-L. Toward a rational photocatalyst design: A new formation strategy of co-catalyst/semiconductor heterostructures via in situ exsolution. *Chem. Commun.* 2018, 54, 1505–1508.

67. Arandiyian, H.; Wang, Y.; Scott, J.; Mesgari, S.; Dai, H.; Amal, R. In Situ Exsolution of Bimetallic Rh–Ni Nanoparticles: A Highly Efficient Catalyst for CO2 Methanation. *ACS Appl. Mater. Interfaces* 2018, 10, 16352–16357.

68. Kwak, N.W.; Jeong, S.J.; Seo, H.G.; Lee, S.; Kim, Y.; Kim, J.K.; Byeon, P.; Chung, S.-Y.; Jung, W. In situ synthesis of supported metal nanocatalysts through heterogeneous doping. *Nat. Commun.* 2018, 9, 4829.

69. Kwon, O.; Sengodan, S.; Kim, K.; Kim, G.; Jeong, H.Y.; Shin, J.; Ju, Y.-W.; Han, J.W.; Kim, G. Exsolution trends and co-segregation aspects of self-grown catalyst nanoparticles in perovskites. *Nat. Commun.* 2017, 8, 15967.

70. Zhu, Y.; Zhou, W.; Ran, R.; Chen, Y.; Shao, Z.; Liu, M. Promotion of Oxygen Reduction by Exsolved Silver Nanoparticles on a Perovskite Scaffold for Low-Temperature Solid Oxide Fuel Cells. *Nano Lett.* 2016, 16, 512–518.

71. Sun, Y.-F.; Zhang, Y.-Q.; Chen, J.; Li, J.-H.; Zhu, Y.-T.; Zeng, Y.-M.; Amirkhiz, B.S.; Li, J.; Hua, B.; Luo, J.-L. New Opportunity for in Situ Exsolution of Metallic Nanoparticles on Perovskite Parent. *Nano Lett.* 2016, 16, 5303–5309.

72. Fuertes, A. Chemistry and applications of oxynitride perovskites. *J. Mater. Chem.* 2012, 22, 3293–3299.

73. Yang, M.; Oró-Solé, J.; Rodgers, J.A.; Jorge, A.B.; Fuertes, A.; Attfield, J.P. Anion order in perovskite oxynitrides. *Nat. Chem.* 2011, 3, 47.

74. Padi, S.P.; Shelly, L.; Komarala, E.P.; Schweke, D.; Hayun, S.; Rosen, B.A. Coke-free methane dry reforming over nano-sized NiO-CeO2 solid solution after exsolution. *Catal. Commun.* 2020, 138, 105951.

75. Gao, Y.; Chen, D.; Sacoccio, M.; Lu, Z.; Ciucci, F. From material design to mechanism study: Nanoscale Ni exsolution on a highly active A-site deficient anode material for solid oxide fuel cells. *Nano Energy* 2016, 27, 499–508.

76. Singh, S.; Zubenko, D.; Rosen, B.A. Influence of LaNiO3 Shape on Its Solid-Phase Crystallization into Coke-Free Reforming Catalysts. *ACS Catal.* 2016, 6, 4199–4205.
77. Fang, F.; Feng, N.; Zhao, P.; Chen, C.; Li, X.; Meng, J.; Liu, G.; Chen, L.; Wan, H.; Guan, G. In situ exsolution of Co/CoOx core-shell nanoparticles on double perovskite porous nanotubular webs: A synergistically active catalyst for soot efficient oxidation. *Chem. Eng. J.* 2019, 372, 752-764.

78. Sun, Y.-F.; Li, J.-H.; Zhang, Y.-Q.; Hua, B.; Luo, J.-L. Bifunctional Catalyst of Core–Shell Nanoparticles Socketed on Oxygen-Deficient Layered Perovskite for Soot Combustion: In Situ Observation of Synergistic Dual Active Sites. *ACS Catal.* 2016, 6, 2710–2714.

79. Ruban, A.V.; Skriver, H.L.; Nørskov, J.K. Surface segregation energies in transition-metal alloys. *Phys. Rev. B* 1999, 59, 15990–16000.

80. Lin, C.; Foucher, A.C.; Ji, Y.; Curran, C.D.; Stach, E.A.; McIntosh, S.; Gorte, R.J. “Intelligent” Pt Catalysts Studied on High-Surface-Area CaTiO3 Films. *ACS Catal.* 2019, 9, 7318–7327.

81. Lai, K.-Y.; Manthiram, A. Evolution of Exsolved Nanoparticles on a Perovskite Oxide Surface during a Redox Process. *Chem. Mater.* 2018, 30, 2838–2847.

82. Jiang, Y.; Geng, Z.; Sun, Y.; Wang, X.; Huang, K.; Cong, Y.; Shi, F.; Wang, Y.; Zhang, W.; Feng, S. Highly Efficient B-Site Exsolution Assisted by Co Doping in Lanthanum Ferrite toward High-Performance Electrocatalysts for Oxygen Evolution and Oxygen Reduction. *ACS Sustain. Chem. Eng.* 2019, 8, 302–310.

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