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Towards the decentralized electrochemical production of H$_2$O$_2$: A focus on the catalysis

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ABSTRACT

H.O. is a valuable, environmentally friendly oxidizing agent, with a wide range of uses, from the provision of clean water to the synthesis of valuable chemicals. The on-site electrolytic production of H.O. would bring the chemical to applications beyond its present reach. The successful commercialization of electrochemical H.O. production requires cathode catalysts with high activity, selectivity and stability. In this Perspective, we highlight our current understanding of the factors that control the cathode performance. We review the influence of catalyst material, electrolyte and the structure of the interface at the mesoscopic scale. We provide original theoretical data on the role of the geometry of the active site and its influence on activity and selectivity. We have also conducted a series of original experiments on (i) the effect of pH on H.O. production on glassy carbon, pure metals, and metal-mercury alloys, and (ii) the influence of cell geometry and mass transport in liquid half-cells in comparison to membrane electrode assemblies.

KEYWORDS

Hydrogen peroxide, electrocatalysis, oxygen reduction reaction, catalyst selectivity, power-to-chemicals, electrochemical synthesis, geometric effects, electronic effects.
1. INTRODUCTION; Current status of H\textsubscript{2}O\textsubscript{2} production

H\textsubscript{2}O\textsubscript{2} is a versatile and environmentally friendly oxidant. It plays a critical role in a remarkably diverse range of applications, including first-aid kits for disinfection, pulp and textile bleaching, wastewater treatment, chemical synthesis, semiconductor cleaning, detergent, and exhaust air treatment (Figure 1). Increased efforts to avoid environmental damage are driving an upswing in demand for H\textsubscript{2}O\textsubscript{2}. The annual production of H\textsubscript{2}O\textsubscript{2} reached 5.5 million t in 2015, significantly exceeding the forecast of 4.3 million t made in 2011.

In this Perspective, we summarize the established anthraquinone method for industrial H\textsubscript{2}O\textsubscript{2} production along with upcoming alternatives, such as direct synthesis and electrochemical synthesis. We review past literature and present new experimental and theoretical data; on this basis, we argue that successful implementation of electrochemical H\textsubscript{2}O\textsubscript{2} production can be realized by carefully tailoring the electrode and electrolyte at the cathode of electrochemical cells.

**Anthraquinone process.** The anthraquinone process (sometimes known as the auto-oxidation process), was a breakthrough in the large-scale production of hydrogen peroxide. It quickly
became the most used process after its development in 1939 by Riedl and Pfleiderer, and the first successful production plant came into use in 1953. It is still the most widely used process and accounts for more than 95% of H₂O₂ production today. It consists of sequential hydrogenation and oxidation steps in an organic solvent, followed by extraction and further distillation, as shown in Figure 2. An anthraquinone derivative, usually 2-alkyl anthraquinone, is used as a reaction carrier. The anthraquinone molecule is first hydrogenated to corresponding hydroquinone under hydrogen with Ni or supported Pd as catalyst. After separation, hydroquinone is oxidized with air to produce H₂O₂ along with anthraquinone molecule. Subsequently, H₂O₂ is extracted from the organic solvent by water to produce an aqueous solution of H₂O₂. Distillation follows to produce concentrated H₂O₂ solution. Anthraquinone molecules in the organic solvent are regenerated and reused in the next cycle.

The major drawbacks of the anthraquinone process are that it requires large infrastructure and that it is a batch method. The large-scale, centralized, production requires additional transportation of a hazardous material. To minimize transportation costs, energy-intensive distillation is required to produce up to 70 wt% H₂O₂. Nonetheless, there are multiple applications where end-users require dilute H₂O₂ solutions. Many applications require < 9 wt% of H₂O₂, such as pulp bleaching, chemical

Figure 2. Schematic of anthraquinone process
synthesis, medical uses, and cosmetic uses. On the other hand, for water treatment, only < 0.1 wt% H₂O₂ is necessary. Highly concentrated H₂O₂ is explosive, and its transportation has caused severe accidents, exemplified by incidents in Helena, Montana, USA in 1989 and in London, England in 2005. Moreover, care must be taken when diluting concentrated H₂O₂. Other drawbacks of the anthraquinone process include (i) the use of large amounts of organic solvents (ii) the degradation of anthraquinone molecules (iii) the need to add stabilizer to prevent the decomposition of concentrated H₂O₂; stabilizers can be undesirable for many consumers, meaning that they need to be tailored for specific applications and industries. The deficiencies of the anthraquinone process are motivating industry and academia alike to develop alternative synthesis methods, thus decentralizing H₂O₂ production, in particular the direct synthesis and electrochemical methods. Despite the differences between the two methods, they do share similar attributes, especially in terms of the catalysis. Therefore, we will introduce the factors controlling the catalysis of the direct synthesis method, before focusing on electrochemical H₂O₂ production.

2. DIRECT SYNTHESIS OF H₂O₂

The direct synthesis of H₂O₂ is a straightforward batch process, where both H₂ and O₂ gases are simultaneously introduced into a liquid medium in the presence of a catalyst (Figure 3). It was first reported as early as 1914. It avoids the need to transport H₂O₂ to site, but does require H₂. Because it involves a mixture of H₂ and O₂, these gases are diluted in N₂ or CO₂ to avoid entering the flammable range; such dilution limits the productivity of the process.

H₂O₂ production comprises the selective hydrogenation of O₂ (Figure 4a). The role of the catalyst should be to sustain high rates of H₂O₂ production while minimizing its further reduction to H₂O. It
should also prevent \( \text{H}_2\text{O}_2 \) decomposition. Most experiments have focused on Pd, or Pd-based catalysts; in particular Hutchings and coworkers have produced seminal works in this area, on Pd-Au and Pd-Sn catalysts. 

The proposed mechanism for direct synthesis is as follows: the reaction starts with a \( \text{H}_2 \) molecule dissociating into hydrogen atoms on the catalyst surface. Subsequently, an \( \text{O}_2 \) molecule adsorbs on the catalyst surface and react with hydrogen atom to form \( \text{*OOH} \) intermediate. The \( \text{*OOH} \) intermediate reacts with another hydrogen atom to form \( \text{H}_2\text{O}_2 \), followed by desorption of \( \text{H}_2\text{O}_2 \) from the catalyst surface.

Density functional theory (DFT) calculations reveal the electronic factors that control the direct synthesis of \( \text{H}_2\text{O}_2 \). Rankin and Greeley showed that the activity and selectivity of the direct synthesis is controlled by the binding energies of \( \text{*O} \) and \( \text{*H} \) (where * denotes species adsorbed onto an active surface site), as shown in the volcano on Figure 4b. The contour map of Figure 4b represents the predicted activity for \( \text{O}_2 \) reduction; it is based on Sabatier’s principle, which states that the optimal catalyst should exhibit intermediate binding to the reaction intermediates. The reason that such a complicated reaction can be described solely by the binding energies of \( \text{*O} \) and \( \text{*H} \) is that the binding energies of the other adsorbed intermediates, such as \( \text{*OH} \) and \( \text{*OOH} \), scale
linearly with that of *O. Thus, metals that exhibit strong binding to *O and *H— such as Ru, Rh, Ni, Co, Os, and Rh — are rate limited by the hydrogenation of *OH. Conversely, metals on the upper side of the volcano, which exhibit weak binding to *H — such as Au and Ag — are rate limited by the dissociation of H. No pure metals occupy the lower right side of the volcano, which is limited by O₂ dissociation and *OOH formation. Other metals — such as Pd, Pt, Cu or Ir — intersect different rate-limiting steps and exhibit the highest activity, hence occupying the peak of the volcano. Not only are these catalysts highly active for O₂ reduction to H₂O₂, but also for the further reduction to H₂O. Consequently, additional criteria are required to identify the most selective catalysts: in particular, they should disfavor the dissociation of the species, O₂, *OOH, and H₂O relative to the desired hydrogenation steps. Such surfaces would occupy the shaded area on the right-hand side of the volcano on Figure 4b. The only pure metal to occupy this shaded area is Au. Notably, Figure 4b are modelled by terraces. More realistically, the surfaces of nanoparticles contain steps and edges, which would favor O-O dissociation, further shrinking the peroxide selectivity window.

The optimal catalyst should have slightly stronger binding energies of *O and *H than Au, while remaining in the selective grey region in Figure 4b. It turns out that AuPd alloys fit these criteria, explaining the experimental interest in these alloys.

According to Hutchings and coworkers, AuPd alloy catalysts exhibit higher H₂O₂ production rates than pure Pd or pure Au, in agreement with the theoretical model in Figure 4b. Figure 5 shows high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images and elemental mapping of calcined AuPd catalysts on three different supports: C, TiO₂, and Al₂O₃. The most active and selective catalyst, AuPd/C, consisted of a homogeneous alloy of AuPd, while the other two catalysts consisted of a Au core with a Pd shell. Curiously, they found the
carbon support alone to be highly active for the unwanted reaction, H₂O₂ hydrogenation. They proposed that the introduction of Au affects the selectivity by blocking impurity sites on the surface.

Figure 4. (a) Reaction pathways for direct synthesis of H₂O₂. (b) Activity contour map and H₂O₂ selective boundaries on 12 transition metal surfaces and three different Pd-Au surfaces for direct synthesis of H₂O₂. White dots, clockwise from top, represent Pd/Au₄Pd/AuPd/Au, Pd/Au/PdAu/PdAu/PdAu, and Pd/Au/Pd/AuPd/Au. Activity volcano contour for direct oxygen reduction is shown in eV, normalized by $kT/h$. Selective H₂O₂ formation is represented by the grey region. Lines represent competition between (1) O₂ hydrogenation and dissociation, (3) H₂O₂ desorption and dissociation, and (4) OOH hydrogenation and dissociation. Free energies of oxygen and hydrogen adsorption are denoted as $ΔG_ρ^*$ and $ΔG_ρ$. Adapted with permission from Ref. 28. Copyright 2012 American Chemical Society.
of the carbon that are responsible for H\textsubscript{2}O\textsubscript{2} decomposition.\textsuperscript{21} This significant finding suggests that controlling selectivity is complex; the factors controlling it cannot be entirely described by the simple Sabatier volcano model depicted by Figure 4b.

Freakley et al. showed that the addition of Sn to Pd catalysts also improves their activity and selectivity for the direct synthesis of H\textsubscript{2}O\textsubscript{2}.\textsuperscript{22} The two metals formed homogeneous alloy nanoparticles, with some coverage of surface SnO. Presumably, Sn has a similar electronic effect to Au in improving the activity of Pd. On the other hand, they suggested that the improved selectivity was due to the encapsulation of small Pd nanoparticles, which would typically catalyse the further hydrogenation.

Halide ions and acid promoters are added to prevent further hydrogenation of H\textsubscript{2}O\textsubscript{2} on Pd catalysts. Halide anions, especially Cl\textsuperscript{-} and Br\textsuperscript{-}, act as a poisoning species and decrease overall activity while increasing H\textsubscript{2}O\textsubscript{2} selectivity. Burch et al. clearly showed the halide effect in direct synthesis using different concentration of NaBr promoter on Pd/C catalyst.\textsuperscript{23} There is no H\textsubscript{2}O\textsubscript{2} production in the absence of Br\textsuperscript{-}; however, upon addition of Br\textsuperscript{-}, H\textsubscript{2}O\textsubscript{2} starts being produced. H\textsubscript{2}O\textsubscript{2} yields increase with increasing concentration of Br\textsuperscript{-}, at the expense of lower hydrogen conversion. However, at high concentrations, Br\textsuperscript{-} blocks surface active sites and both H\textsubscript{2} conversion and H\textsubscript{2}O\textsubscript{2} yield drastically diminish. Other researchers also observed halide effect on direct synthesis.\textsuperscript{26,30,32} The addition of acid can increase the stability of H\textsubscript{2}O\textsubscript{2} since H\textsubscript{2}O\textsubscript{2} decomposition is base-catalyzed.\textsuperscript{26,30,32} For this reason, the use of acidic support materials increased the H\textsubscript{2}O\textsubscript{2} yield.\textsuperscript{24} For the direct synthesis of H\textsubscript{2}O\textsubscript{2}, the addition of both halides and acid to Pd catalysts is commonplace. However, the subsequent need to remove these toxic additives is undesirable.
Hutchings and coworkers are implementing the direct synthesis into domestic greywater treatment systems. Greywater is domestic wastewater from bathrooms, laundry, and kitchen sinks. It could be reused for flushing, gardening, and washing after on-site treatment. H,O is well suited to such applications. The process would require an onsite water electrolyser to produce the H₂ and O₂, coupled to the direct synthesis reactor.

3. ELECTROCHEMICAL H,O PRODUCTION

The electrochemical production of H,O proceeds via the cathodic reduction of O₂. The reaction can either produce the desired H,O via the 2-electron pathway or H₂O via the 4-electron pathway.
(c.f. the direct synthesis process, on Figure 4). The overall reactions and thermodynamic potentials versus reversible hydrogen electrode (RHE) are as follows:

At pH < 11.6

\[ \text{O}_2 + 2 \text{H}^+ + 2 \text{e}^- \rightarrow \text{H}_2\text{O} \quad (U_{\text{O}_2/\text{H}_2\text{O}} = 0.7 \text{ V vs RHE}) \] (1)

\[ \text{O}_2 + 4 \text{H}^+ + 4 \text{e}^- \rightarrow 2 \text{H}_2\text{O} \quad (U_{\text{O}_2/\text{H}_2\text{O}} = 1.23 \text{ V vs RHE}) \] (2)

However, above the pKa of H$_2$O$_2$, which is 11.6, the product of the 2-electron pathway changes from H$_2$O$_2$ to HO$_2^-$. Consequently, should we consider pH 13:

\[ \text{O}_2 + \text{H}_2\text{O} + 2 \text{e}^- \rightarrow \text{HO}_2^- + \text{OH}^- \quad (U_{\text{O}_2/\text{HO}_2^-} = 0.74 \text{ V vs RHE}) \] (3)

\[ \text{O}_2 + 2 \text{H}_2\text{O} + 4 \text{e}^- \rightarrow 4 \text{OH}^- \quad (U_{\text{O}_2/\text{OH}^-} = 1.23 \text{ V vs RHE}) \] (4)

In this article, we consider the selectivity towards H$_2$O$_2$ as the Faradaic efficiency, $\lambda_{\text{Faradaic}}$, defined as the ratio of charge converted to H$_2$O$_2$, to the total charge transferred.

Prior to the invention of anthraquinone process, electrolysis constituted the primary source of commercial H$_2$O$_2$. In 1853, Meidinger synthesized hydrogen peroxide by electrolysis of aqueous sulfuric acid. Sulfuric acid, H$_2$SO$_4$, was first oxidized to peroxodisulfuric acid, H)$_2$S$_2$O$_8$, which subsequently hydrolysed to H$_2$O$_2$. The first H$_2$O$_2$ plant using this process was implemented in 1908 in Weissenstein. Later, sulfuric acid was substituted by ammonium sulfate; the annual production of H$_2$O$_2$ using this process reached 35,000 t in 1950.37

The electrochemical reduction of O$_2$ was first reported as a means of producing H$_2$O$_2$ in the 1930s by Berl;38 it used activated carbon as a cathode, achieving 90% Faradaic efficiency. In the 1980s, Dow and Huron Technologies, Inc. adopted this method for the on-site production of dilute alkaline H$_2$O$_2$, Huron-Dow process (Figure 6a). Since dilute alkaline H$_2$O$_2$ is used for the pulp and paper bleaching process, neither neutralization nor distillation is necessary, making the Huron-Dow process commercially viable. The Huron-Dow process was commercialized in 1991 and it is
close to being competitive to the anthraquinone process. The major disadvantage of the Huron-Dow process is the high alkalinity of the working solution. H₂O₂ readily decomposes in alkaline media, therefore it has to be used immediately. Additional disadvantages of this process include (i) the need to neutralize the solution for most applications, (ii) carbonate formation from CO₂, (iii) the corrosion induced by the highly alkaline environment and (iv) the high Ohmic resistance, largely due to the ceramic membrane used to separate the anode and cathode.

The electro-Fenton process is a recent variant of the Huron-Dow process. In the Fenton method, a mixture of H₂O₂ and Fe²⁺ ions produce hydroxyl radicals (·OH); the hydroxyl radicals are then used to remove persistent organic pollutants. In the electro-Fenton process, H₂O₂ is produced in-situ using electrochemistry, and Fe²⁺ is added to produce hydroxyl radicals (Figure 6b). A typical electro-Fenton process consists of two electrodes in an undivided cell with aqueous Na₂SO₄ electrolyte at pH 3. The optimal pH for the Fenton method is pH 3; many research groups have focused on this particular pH for efficient removal of pollutants. The H₂O₂ concentrations produced by the electro-Fenton process range from 10 ppm to 2 %. The most frequently used cathode catalysts are carbon based materials such as graphite, carbon nanotubes, carbon fiber, carbon black, and carbon sponge. Nitrogen or oxygen functional groups are sometimes introduced to carbon materials to improve catalytic properties. Polytetrafluoroethylene (PTFE, Teflon®) is often used with carbon materials as a binder, and to provide hydrophobicity. The electro-Fenton process is very effective, even with the most persistent organic pollutants. It has many advantages over the conventional Fenton process, where H₂O₂ and Fe²⁺ are added to the polluted water. In the electro-Fenton process, H₂O₂ is generated on-site and Fe²⁺ can be regenerated at the cathode (Figure 6b), therefore the required concentration of iron ions is an order of magnitude lower than the conventional Fenton method.
Microbial electrochemical cells can also produce H₂O₂ (Figure 6c). An aqueous solution containing acetate, or even wastewater, is used as a feed source to the anode. Microorganisms attached to the anode oxidise those organic solution phase species. In contrast to the electro-Fenton process, a cationic membrane separates anode and cathode electrolyte. Microbial electrochemical cells release electrical energy, hence function as fuel cells at the same time as producing H₂O₂.

**Figure 6.** Schematic illustrations of different means of electrochemical H₂O₂ production.

(a) Huron-Dow process, cathodic O₂ reduction in alkaline media. (b) Electro-Fenton process. (c) Microbial electrosynthesis. (d) Electrolytic H₂O₂ production using a PEM.
However, additional electrical energy is commonly added to enhance the rate of hydrogen peroxide production. Carbon-based materials such as carbon black, graphite, carbon cloth or a combination are used as cathode catalysts, similar to those used in the electro-Fenton process. Although these materials are highly selective, they exhibit a very low activity, meaning a large overpotential is required. Microbial electrochemical cells yield H₂O₂ concentrations ranging from 80 ppm to 1 %. That way, H₂O₂ can be produced with energy scavenged from wastewater using microbial electrosynthesis.

As an aside, it is worth highlighting a recently investigated variant of electrochemical H₂O₂ production: through the anodic oxidation of water, albeit only consuming two electrons. Four electrons are required for the more ubiquitous variant of water oxidation: O₂ evolution. In principle, it could enable the production of valuable chemical at the anode of electrolyser, rather than wasting energy by producing O₂, (cf. Figure 6d). Shi et al. experimentally tested four oxide catalysts for anodic H₂O₂ production, chosen on the basis of DFT calculations. BiVO₄ showed highest Faradaic efficiency of 70 % without light illumination, and 98 % with 1 sun illumination, albeit at low current densities.

Yamanaka and co-workers pioneered the electrochemical production of H₂O using proton exchange membrane (PEM) electrolytes. In their first work in this area, they set up a PEM fuel cell type configuration, where H₂ was oxidized at the anode and O₂ at the cathode. The proton exchange membrane was based on Nafion, which has a highly acidic pH. They later adapted this design to an electrolyser setup, as shown in Figure 6d, where O₂ evolution was used as a source of protons: this configuration negates the need to separately handle, produce (and possibly transport) H₂. In a PEM configuration, the anode and cathode catalysts are in direct contact with the solid electrolyte. Both the cathode and anode are immersed in liquid water (Figure 6d). They tested
several different cathode catalysts, including vapor-grown carbon fiber (VGCF), activated carbon with VGCF, oxidized activated carbon with VGCF, Co-N, and Mn-N. Using Co-N/C as a cathode catalyst, Yamanaka and coworkers demonstrated that they could produce aqueous solutions of H₂O₂ at concentrations as high as 18.7 wt% H₂O₂, with a Faradaic efficiency of 55%.

A key advantage of using the PEM configuration is that the H₂O₂ produced is H₂O₂ in pure water, as shown in Figure 6d. The product is thus ready to use; the other synthesis methods described above typically produce the H₂O₂ in media containing other compounds, necessitating additional purification steps. Winton et al. have shown that neutral H₂O₂ solution can be produced in a continuous-flow process adopting a PEM fuel cell configuration. Flow processes are less cumbersome than batch methods, reducing operating costs. As such, the PEM method is particularly suitable for small-scale, on-site, synthesis of dilute and neutral H₂O₂. Moreover, unlike the direct synthesis method, the potentially flammable mixture of H₂ and O₂ can be avoided. The technology also capitalizes upon ongoing advances in PEM electrolyser and fuel cell technology.

Much the same as for the direct synthesis process, the catalyst governs the efficiency of electrochemical H₂O₂ production. As such, a rapidly increasing body of research is being devoted to the catalysis of O₂ reduction to H₂O₂. Below, we summarize our current understanding of this reaction. Moreover, going beyond the scope of other research papers, we review the challenges in implementing the catalysts into real devices.

**3.1. Importance of catalysis in controlling H₂O₂ production.** The performance of the catalyst strongly influences the overall cost of an electrochemical technology; as such, improvements in catalyst efficiency can be the main driver in major cost reductions. The total cost per mole of
hydrogen peroxide ($C_{\text{total}}$) can be expressed as the addition of two key parameters: electricity and capital cost: $C_{\text{total}} = C_{\text{electricity}} + C_{\text{capital}}$.

The total cost of electricity per mole H$_2$O$_2$ produced, $C_{\text{electricity}} = p_{\text{electricity}}UnF/\lambda_{\text{Faradaic}}$, where $p_{\text{electricity}}$ is the cost per unit energy of electricity ($\$ \text{ J}^{-1}$), $U$ is the cell potential (V), $n = 2$, the number of electrons transferred per H$_2$O molecule, $F$ is Faraday’s constant (96485.3 C mol$^{-1}$), and $\lambda_{\text{Faradaic}}$ is the Faradaic efficiency, defined as the ratio of charge converted to H$_2$O$_2$, to the total charge transferred. The capital costs per mole H$_2$O$_2$ produced, $C_{\text{capital}} = p_{\text{capital}}nF/jt\lambda_{\text{Faradaic}}$, where $p_{\text{capital}}$ is the capital cost per unit electrode area ($\$ \text{ cm}^{-2}$), $n = 2$, the number of electrons transferred per H$_2$O molecule, and $t$ is the total operating time of the plant over its lifetime (s), and $j$ is the current density (A cm$^{-2}$). Neglecting operations and maintenance costs, the total costs, $C_{\text{total}} = \frac{p_{\text{electricity}}UnF}{\lambda_{\text{Faradaic}}} + \frac{p_{\text{capital}}nF}{jt\lambda_{\text{Faradaic}}}$. Since the denominator for both electricity costs and capital costs contain the term, $\lambda_{\text{Faradaic}}$, it is clear that the Faradaic efficiency plays a significant role in the economic efficacy of the process.

Costs related to electricity can be reduced by lowering $U$. The standard thermodynamic potential for electrolytic H$_2$O$_2$ production, $U_{\text{cell}}^0 = U_{0}^{O_2/H_2O} - U_{0}^{O_2/H_2O_2} = 0.53$ V where the standard potential for O$_2$ evolution $U_{0}^{O_2/H_2O} = 1.23$ V and H$_2$O$_2$ production, $U_{0}^{O_2/H_2O_2} = 0.7$ V. However, overpotentials for both half-cell reactions result in $U$ being significantly larger than 0.53 V. Notably, $j$ increases as a function of $U$. Consequently, there could be a pay-off in operating the electrolyser at high potential losses in order to maximize $j$; the exact extent of this payoff will depend on the ratio of $p_{\text{electricity}}$ to $p_{\text{capital}}$. Even so, the ideal cathode catalyst should be able to sustain high current densities without compromising on potential losses, or overpotentials. Importantly, costs related to capital can also be minimized by increasing the operating lifetime of
the system, \( t \), which highlights the relevance of catalyst stability. In the continuing section, we will discuss the design-criteria for efficient \( \text{H}_2\text{O}_2 \) production catalysis.

4. TAILORING THE ELECTRODE; Fundamental aspects of the 2 electron process to produce \( \text{H}_2\text{O}_2 \).

4-1. Experimental state-of-the-art for electrochemical \( \text{H}_2\text{O}_2 \) production. As stated earlier, Yamanaka and co-workers produced \( \text{H}_2\text{O}_2 \) using PEM fuel-cell or PEM electrolyser-like devices (Figure 6d). The optimization of the cathode catalyst was one of their priorities. They first explored different metal catalysts and Au showed higher Faradaic efficiency than Pd, Pt, Ir, and Rh.\(^{62,64}\) However, carbon materials were very efficient showing similar\(^{62}\) or even better\(^{64}\) Faradaic efficiency than Au. They also used graphitic carbon materials, vapor-grown carbon fibers (VGCF),\(^6\) activated carbon with VGCF,\(^6\) oxidized activated carbon with VGCF,\(^6,66\) and metal-nitrogen/carbon (M-N/C) catalysts, Co-N,\(^6,66\) and Mn-N.\(^7\) Notably, several reports show that the oxidative treatment of carbon can yield higher rates of \( \text{H}_2\text{O}_2 \) production in a fuel cell configuration as well as in the electro-Fenton process.\(^5,65\) Incorporating phenol groups onto carbon electrodes improves the rates of \( \text{H}_2\text{O}_2 \) production in a PEM electrolyser setup.\(^66\)

Unlike Yamanaka et al, Sánchez-Sánchez and Bard quantified \( \text{H}_2\text{O}_2 \) production from oxygen reduction reaction (ORR) in 0.5 M \( \text{H}_2\text{SO}_4 \) using scanning electrochemical microscopy on different metal surfaces.\(^73\) The technique enabled fast screening of electrochemical ORR activity along with selectivity. Hg showed the highest selectivity, followed by Au, Ag, Cu, and AuCu. Conversely, Pt, and PdCo followed the 4e- reduction pathway.

The rotating ring-disk electrode (RRDE) in a three electrode cell using liquid electrolytes is a simple, yet powerful, electrochemical method to quantitatively measure the production of \( \text{H}_2\text{O}_2 \).
from oxygen reduction (Figure 7). In contrast to catalytic tests in real electrochemical devices, RRDE tests are simpler to optimize and yield high reproducibility on a laboratory-scale.\textsuperscript{74,75} Moreover, they are far more inexpensive than scanning electrochemical microscopes. Oxygen reduction takes place at the disk electrode; the catalyst can either be a bulk, planar extended surface or a thin film of supported nanoparticles.\textsuperscript{74,75} H\textsubscript{2}O\textsubscript{2} produced at the disk electrode is radially transferred to the concentric platinum ring electrode by the forced convection caused by the rotating motion of the electrode. Subsequently, H\textsubscript{2}O\textsubscript{2} is oxidized back to O\textsubscript{2} at the ring electrode. We can calculate the selectivity the disk current and ring current by two means (i) the Faradaic efficiency, which we defined earlier:

\[
\text{Faradaic efficiency (\%)} \lambda_{\text{Faradaic}} = \frac{i_R}{i_D} \times 100 \tag{5}
\]

, where \(i_r\) and \(i_d\) are ring and disk current respectively, and \(N\) is collection efficiency of RRDE, or (ii) in terms of the fraction of O\textsubscript{2} used for H\textsubscript{2}O\textsubscript{2}.

\[
\text{O}_2 \text{ efficiency (\%)} \lambda_{O_2} = \frac{2 \times \frac{i_R}{N}}{i_D + \frac{i_R}{N}} \times 100 \tag{6}
\]
For the current paper, we have exclusively reported the selectivity in terms of Faradaic efficiency, as we take the view that it is the more relevant metric; this contrasts from our earlier works, where we provided the O₂ efficiency.⁷⁶,⁷⁷

Numerous experimental groups have tested catalyst materials using the RRDE set-up. Figure 8a is a comparison of different electrocatalysts for H₂O₂ production, in the form of a Tafel plot. All measurements are conducted in aqueous solutions of HClO₄ or H₂SO₄, with the exception of the glassy carbon (GC), which was conducted in alkaline solution, as we will discuss in Section 5-1. Figure 8b shows the Faradaic efficiency of the same catalysts. These include (i) pure metal surfaces⁷⁶ (ii) alloys⁷⁶,⁷⁷,⁷⁸,⁷⁹ (iii) single atom Pt-based catalysts, i.e. isolated Pt monomers anchored on inert supports,⁸⁰,⁸¹ (iv) porphyrin and porphyrin like structures, Co-N/C⁸²,⁸³ and Mn-N/C⁷¹ (v) anthraquinone modified carbon,⁸⁴ and (vi) N/C.⁸⁵ In terms of catalytic activity, Pd-Hg, which we discovered in an earlier study, is the superior catalyst in acid; it showed a Faradaic selectivity of 88 %, it was also highly stable in accelerated degradation tests.⁷⁷ However, as shown in Figure 8b, several other catalysts show a peak Faradaic selectivity of 100 %, including Au(pc), Ag-Hg(pc) and Co-N/C. The latter is of particular interest, because the activity is amongst the highest in Figure 8a. On the other hand, the stability of porphyrin and porphyrin-like structures tend to be low.⁸⁶,⁸⁷ High temperature annealing in inert atmosphere results in a significantly increased stability; however, the heat treatment tends to decrease the selectivity towards H₂O₂.⁸⁷,⁸⁸

4-2. Trends in oxygen electroreduction. The experimental determination of the oxygen reduction reaction mechanism is complicated by challenges in probing the reaction intermediates. As such, DFT-based models have been most fruitful in elucidating the reaction;⁸⁹–⁹² they show
particularly good agreement with experiments in acidic media.\textsuperscript{77,93,94} Herein, we will make use of these models.\textsuperscript{92} The 2-electron pathway to H\textsubscript{2}O\textsubscript{2} proceeds as follows:

\[
O_2 + * + (H^+ + e^-) \rightarrow * \text{OOH} \quad (7)
\]
\[ \text{*OOH} + (\text{H}^+ + e^-) \rightarrow \text{H}_2\text{O}_2 \]  \hspace{1cm} (8)

where * denotes an unoccupied active site or species adsorbed onto an active surface site. On the other hand, *OOH can undergo two different dissociation steps:

\[ \text{*OOH} + (\text{H}^+ + e^-) \rightarrow \text{*O} + \text{H}_2\text{O} \]  \hspace{1cm} (9)

\[ \text{*OOH} + * \rightarrow \text{*O} + *\text{OH} \]  \hspace{1cm} (10)

which may lead to 4-electron (4e-) reduction to H\(_2\)O. The produced H\(_2\)O\(_2\), from (8), may well be dissociated into two *OH or undergo further proton-electron transfer before it desorbs from the surface. Moreover, H\(_2\)O in the bulk solution can re-adsorb on the active site and dissociate:

\[ \text{H}_2\text{O}_2 + 2* \rightarrow \text{*OH} + *\text{OH} \]  \hspace{1cm} (11)

or electrochemically be reduced further:

\[ \text{H}_2\text{O}_2 + (\text{H}^+ + e^-) + * \rightarrow \text{*OH} + \text{H}_2\text{O} \]  \hspace{1cm} (12)

The dissociation intermediates, *OH and *O, can be further reduced, closing the reduction process by producing H\(_2\)O via 4-electron reduction:

\[ \text{*O} + (\text{H}^+ + e^-) \rightarrow \text{*OH} \]  \hspace{1cm} (13)

\[ \text{*OH} + (\text{H}^+ + e^-) \rightarrow \text{H}_2\text{O} + * \]  \hspace{1cm} (14)

Similar to the direct synthesis method, the question of whether H\(_2\)O or H\(_2\)O\(_2\) is produced depends on the ability of the catalyst to dissociate the oxygen-oxygen bond.

Electronic effects completely control the catalytic activity and partially control the catalytic selectivity. We discussed such effects earlier in this article for the case of the direct synthesis method (Figure 4b). However, in contrast to the direct synthesis method, the catalyst from which
H. O. is produced does not need to dissociate H.; protons would be produced separately at the cathode. This simplifies the Sabatier volcano analysis: only the binding energy of one O-containing intermediate is needed to describe the overall trends. Figure 9a is the Sabatier volcano for oxygen reduction for metal surfaces and metal-nitrogen/carbon (M-N/C, inset of Figure 10) structures. The green lines in Figure 9a derive from the thermodynamic equilibrium for the different limiting steps in the 2 electrons reduction to H. O. For a given *OOH adsorption energy, they allow extrapolation of the theoretical minimum overpotential required by each catalyst. The step of O₂ reduction to *OOH limits the reaction at the weak binding, right-hand leg of the volcano. Conversely, *OOH reduction to H. O. limits the strong binding, left-hand leg. The most active catalyst for H. O. production would sit at the peak of the 2-electron volcano. The black lines represent the limiting potentials for the 4-electron volcano for H. O. production. To the left of the peak of the 2-electron volcano, the limiting potentials of the 4-electron route are always more positive, i.e. there is a greater driving force for H. O. production than H. O. production for strong binding catalysts. To the right of the peak of the 2-electron volcano, the limiting potential for both pathways overlap. Amongst the pure metal surfaces, only Au sits on the weak binding leg; amongst the M-N/C structures, Cu-N/C, Ni-N/C, Pd-N/C, Pt-N/C also lie on the weak binding leg. We also report in Figure 9a the data points for Hg and graphene surfaces. Hg atoms were immobilized in a face-centred cubic (FCC) structure, although under real reaction conditions we acknowledge it is in liquid phase.

According to Figure 9a, no metal surface or M-N/C structure has the optimal electronic structure to exhibit highest possible activity for H. O. production in Figure 9a. Guided by a theoretical screening study, we discovered that we could tune the *OOH binding of Pt and Pd towards optimal values by alloying with Hg, resulting in a high activity for H. O. production. The outcome is
Figure 9. (a) Sabatier volcano plots for electrochemical oxygen reduction for closely packed pure metal slabs (in blue) and M-N/C structures (in red), obtained from DFT calculations. The limiting potential is plotted as a function of $\Delta G_{\text{OOH}}$. The green line represents 2-electron reduction, and the black line represents 4-electron reduction. The volcanoes are based on an earlier model; the individual data points represent original data produced for the current publication. M-N/C catalysts lying to the right of the horizontal red band bind $^\ast$O sufficiently weak to thermodynamically favor the 2 electron pathway to H$_2$O; pure metal catalysts lying to the right of the horizontal blue band bind $^\ast$O sufficiently weak to thermodynamically favor the 2 electron pathway to H$_2$O. These boundaries are shown as bands, rather than lines to represent the inherent uncertainty in the model. (b) Experiment versus theory for pure metals and metal alloys, adapted from Ref 77. The solid line shows the limiting potential from DFT, also shown in a. Circles represents potential required to reach kinetic current of 1 mA/cm$^2$ on polycrystalline electrodes.

represented on Figure 9b, where we plot the experimental potential required to drive 1 mA/cm$^2$ as a function of the theoretical $^\ast$OOH binding energy for both Hg-based alloys and pure metals. The experiments agree well with the Sabatier volcano: Pd-Hg, the most active catalyst, lies at the peak.
However, the origin of the high selectivity of Hg-alloys and some of the other catalysts described above is not purely due to electronic effects; geometric effects also play a role. Interestingly, these seem to play a much stronger role in determining selectivity for the electrochemical process than in the direct synthesis method (see section 2). Regardless of whether O₂ reduction proceeds via the chemical or the electrochemical dissociation of *OOH, *O will constitute one of the dissociation products on the way to H₂O, equation (9) and (10). Thus, the destabilization of the *O intermediate with respect to H₂O₂ (the free energy of which is constant at 3.56 eV, relative to H₂O) should increase selectivity. The preferred adsorption sites of *O are the hollow or bridge site on metal surfaces, whereas the preferred adsorption site of *OOH is the atop site. Consequently, adsorption on a single site would constrain the adsorption to the atop site, destabilizing all intermediates, albeit in different ways. While destabilization of *OOH results in activity loss, a weaker *O binding energy results in a significantly improved selectivity. We clarify such a phenomenon using the DFT-based plot on Figure 10: it shows that the free energy of *O adsorption, ΔG_{*O}, as a function of the free energy of adsorption of *OOH, ΔG_{*OOH}, for a number of different surfaces. Porphyrin type catalysts (M-N/C) are shown in red, while face-centred cubic (FCC) metal (111) terraces are shown in blue. We have fitted the trend for each of the two classes of material; *O adsorption is ~ 0.7 eV weaker on a M-N/C structure, in comparison to a FCC (111) surface with the same *OOH adsorption energy. The horizontal dashed line demarcates ΔG_{H₂O₂}, the free energy of H₂O₂, relative to H₂O. In order for a catalyst to thermodynamically favor H₂O₂ production, relative to H₂O, the *O formation (c.f. equation 9) should be greater than ΔG_{H₂O₂}. Only the catalysts lying above the dashed line on Figure 10, such as Cu-N/C, Ni-N/C, Pd-N/C and Pt-N/C, present a greater thermodynamic drive to H₂O₂ desorption rather than *O formation. On M-N/C catalysts, the lack of contiguous metal sites would prevent the chemical dissociative mechanism.
described by equation (10), limiting the possible routes to H₂O. Similarly, on M-N/Cs the decomposition of H₂O is inhibited; the dissociative chemical re-adsorption in equation (11) cannot happen without two neighbor adsorption sites. On metal slabs instead, active sites are closely packed and the chemical dissociations in equations (10) and (11) are feasible. Notably, equation 12 does not involve the formation of *O; the selectivity is directed by the affinity towards *H₂O adsorbate and could be significant at high peroxide concentrations. The dashed line in Figure 10, corresponding to the Free energy of H₂O₂ under standard conditions relates to the red and blue vertical bands on Figure 9a: M-N/C structures lying to the right of the vertical red band favor the 2-electron pathway over the 4-electron pathway; closely packed metal surfaces to the right of the blue band favor the 2-electron pathway over the 4-electron pathway. Curiously, this theoretical thermodynamic analysis would suggest that several catalysts, such as Co-N/C or Au, should not be selective to H₂O₂ production. However, as shown in Figure 8, RRDE experiments show that in 0.1 M HClO₄, these catalysts are indeed highly selective to H₂O₂ production. This discrepancy could suggest that additional kinetic barriers exist in acid electrolyte, that serve to preserve the O-
O bond and favor H₂O production. Moreover, we note that the free energy of H₂O on Figure 10 is under standard conditions; at lower concentrations the vertical red and blue lines on Figure 9a would shift to the left. To the contrary, more accurately defined solvation effects may shift the red line to the right. Nonetheless, our new DFT simulations describe a key thermodynamic trend: catalysts that exhibit weak binding to *O, relative to the H₂O energy level, should favor H₂O production.

Collman, Anson and coworkers provided an elegant experimental demonstration of geometric versus electronic effects, albeit in three dimensions, almost four decades ago. Figure 11 shows RRDE measurements of a monomeric cobalt porphyrin in comparison to a di-cobalt face-to-face porphyrin. Cobalt porphyrins consist of an active Co atom surrounded by less reactive N atoms, i.e. a prototypical isolated active site (inset of Figure 11a). However, in the di-cobalt face-to-face porphyrin, two porphyrin layers are adjacent to each other (inset of Figure 11b) with a 4Å distance. The regular porphyrin structure is selective for H₂O production, with high currents at the ring of the RRDE. The di-cobalt structure has high currents at the disk and much lower currents at the ring, revealing lower selectivity to H₂O, and a high activity for H₂O production. We anticipate that the binding to *OOH is the same in the Co of both structures; hence we can neglect electronic effects. We attribute the high selectivity of the monomeric porphyrin to the presence of an isolated active site. However, in the di-cobalt face-to-face porphyrin the O₂ molecule would adsorb between
the two adjacent Co atoms, as shown in the schematic figure, allowing it to be dissociated. Hence the difference between the two structures is due to geometric effects.

In addition to the above example, there are numerous reports of Co-N/C type structures being used for H₂O₂ production (also compare with Figure 9). Many research groups have investigated metal porphyrin type catalysts to replace Pt catalysts in fuel cell cathodes for the 4e- pathway. Fe-N/C catalysts are the most well-known catalysts for this purpose. In M-N/C catalysts, the composition of the reactive metal atom, the ligand structure, the redox potential of the metal ligand couple, the loading, the carbon support, and the thermal treatment can contribute to changes in activity and selectivity for the ORR.

There are many other strategies to realize isolated active sites. One such example is by alloying active atoms with inert atoms. For instance, alloying metals such as Pt and Pd with Hg not only
tune the *OOH binding of noble metals (as discussed above), but also leads to the formation of a self-organized surface structure to form isolated active atoms of Pt, surrounded by inert atoms, Hg. Adopting this strategy, we showed that both PtHg, and PdHg, exhibited a high selectivity. This phenomenon is also the origin of the high selectivity of AuPd electrocatalyst alloys. Another means of producing isolated sites is to cover Pt nanoparticles with an inert material, such as amorphous carbon. Single-atom catalysts, e.g. isolated active atoms anchored on supports, also benefit from geometric effects. Single-atom catalysts of Pt on titanium nitride (TiN), titanium carbide (TiC), and sulphur doped carbon have shown high selectivity toward H₂O₂.

Aside from the above electrodes, which consist of at least one metallic element, carbon electrodes are also selective for H₂O₂ production, albeit with very low activity, which we attribute to the inherently weak interaction between C and *OOH; as demonstrated by the graphene point at 5.24 eV *OOH binding energy in Figure 9a, this material binds the intermediates weaker than any of the other materials calculated. Additional treatments can increase the activity of carbon catalysts, such as the introduction of anthraquinone molecules, in analogy to the anthraquinone process. Another route is to functionalize carbon with nitrogen or oxygen functional groups. Compensating for its low intrinsic activity, carbon is inexpensive and can be easily produced in a high surface area form. For this reason, carbon materials have been widely used in the synthesis of H₂O₂ in electro-Fenton process and in microbial electrochemical cells (see section 3).

5. TAILORING THE ELECTROLYTE; pH effect

5-1. pH effect on activity and selectivity for H₂O₂. With the advent of hydroxide conducting polymeric membranes, there is increased interest in catalyzing O₂ reduction to H₂O₂ and H₂O in alkaline—as opposed to acidic—media. In Section 4, we established that in acid, the overall
trends in O2 reduction are well described by DFT-based models, which focus on the thermodynamics of each coupled proton electron transfer. Should we consider the adsorption of the oxygen reduction intermediates, *OH, *OOH and *O, to be controlled by the equilibrium between O2, H2O, protons and electrons, then the overall thermochemistry of oxygen reduction should be largely pH-independent on the RHE scale.123,124 However, experiments suggest that in base, some key trends differ significantly from acid.125 Pt-based surfaces typically follow the 4-electron route to water, except at very negative potentials where the surface is covered with *H.126 As we showed in a very recent paper, around the peak of the four electron volcano, the binding to reaction intermediates controls the activity in alkaline media in a similar means to acid: low index facets of Pt, Pt alloys and Au(100) are well described by the Sabatier volcano model.127 However, stepped surfaces and nanoparticulate Pt seems to be less active in alkaline media than low index facets,128,129 despite exhibiting the optimal binding to OH. The oxygen reduction activity of Pt-based surfaces is roughly pH independent on the RHE scale, varying by up to an order of magnitude between pH 1 and pH 13.126,130 The activity of Pt also changes somewhat as a function of electrolyte cation, even at constant pH.127,131 Conversely, Ag-based surfaces shows a much stronger pH dependence than Pt: for instance, Ag(111) it is quite selective and active for the 2-electron route to H2O in acidic media.77 In alkaline media, it shows high oxygen reduction activity for the 4-electron pathway; for that reason, Ag has been used in alkaline fuel cells.132,133 Au is similar to Ag: in acidic media most Au-based catalysts are selective to the 2-electron pathway and fairly inactive.77 In alkaline media, Au surfaces are generally more active and selective to the 4-electron route; the (100) facet is particularly active.134,135

Carbon-based catalysts show an even more pronounced pH dependence than Au or Ag. Jaramillo and coworkers demonstrated that in 0.1 M KOH, glassy carbon shows exceptionally high activity
In this Section, we aim to establish the differences in activity and selectivity between acid and base for oxygen reduction to H₂O. We have tested several different extended surfaces, including Pt(pc), Pt-Hg, Ag(pc), Ag-Hg and glassy carbon, using RRDE measurements in 0.1 M HClO₄ and 0.1 M KOH measurements. Several, but not all of these surfaces, are reported elsewhere.\textsuperscript{142–146}

Figure 12. Oxygen reduction on Pt-Hg(pc) using a rotating ring-disk electrode. a) Measurement in 0.1 M HClO₄, b) Measurement in 0.1 M KOH. All data taken at 50 mV/s and 1600 rpm at room temperature. Data for (a) is previously reported in Ref \textsuperscript{76}, and (b) is original data for H₂O production—in particular when it is annealed in air.\textsuperscript{16} Conversely, in acid, glassy carbon is so inactive\textsuperscript{75,137–139} that it would not even lie on the Tafel plot on Figure 8a; it only shows a measureable current below 0.2 V RHE. Indeed, the improved selectivity and activity of carbon at high pH motivated Gyenge et al to add cationic surfactants to the electrolyte.\textsuperscript{140,141} In summary, it seems that the most weak-binding surfaces (see Figure 9a) show the strongest pH dependence.
However, by testing all the surfaces in a single study, we aim to provide benchmark performance data. On this basis, we discuss possible reasons for the phenomena we observe.

On Figure 12a we present O$_2$ reduction on polycrystalline Pt-Hg in 0.1 M HClO$_4$, which we reported previously, while in Figure 12b we show new data in 0.1 M KOH. In 0.1 M HClO$_4$, we achieved up to 85% Faradaic efficiency and high activity. In contrast, in 0.1 M KOH, the catalyst shows much lower selectivity and lower peroxide current densities; however, it is fairly active to the 4-electron route, reaching the transport limiting current at around 0.7 V.

**Figure 13.** Oxygen reduction on (a), (b) Ag and (c), (d) Ag-Hg using a rotating ring-disk electrode. (a), (c) Measurement in 0.1 M HClO$_4$. (b), (d) Measurement in 0.1 M KOH. All data taken at 50 mV/s and 1600 rpm at room temperature. Original data
On Figure 13a and b we present data for polycrystalline Ag. We observe a Faradaic efficiency to H₂O₂ as high as 100% in 0.1 M HClO₄, which decreases with increasing overpotential. Conversely, in 0.1 M KOH, the catalyst is almost completely selective to H₂O production. Marković and co-workers reported qualitatively similar data for Ag(111), albeit with lower selectivity to H₂O in 0.1 M HClO₄. Ag-Hg, shown on Figure 13 (c) and (d), shows remarkably similar behavior to Ag. In 0.1 M HClO₄, it shows 100% Faradaic efficiency to H₂O across the entire potential range, albeit with very similar activity to Ag; in 0.1 M KOH, it is highly active and completely selective towards the 4-electron route to water. In our earlier study, we attributed the activity of Ag and Ag-Hg towards H₂O₂ production in 0.1 M HClO₄ to the terraces. We proposed that on Ag-Hg, all the Hg resided on undercoordinated sites, which would be the active sites for H₂O₂ reduction to H₂O, explaining the improved activity. Presumably, in base, the terraces are also active for H₂O production.

In Figure 14a, the glassy carbon (GC) electrode in acidic electrolyte showed very poor activity, though its Faradaic efficiency was above 85%. In alkaline solution, Figure 14b, the GC electrode is not only active but also highly selective, showing above 90% Faradaic efficiency, over the entire potential range studied. The high activity and selectivity of carbon makes it a suitable catalyst for alkaline H₂O₂ production (Figure 6a). Inspired by earlier precedents, we also tested the effect of annealing the electrode in air at 500 °C for 10 h. Annealing the GC increased the ORR activity significantly in acidic and alkaline solutions, as shown in Figure 14 (c), (d). In acidic solution, the Faradaic efficiency decreased by about 10% after annealing process. In alkaline solution, the selectivity was just as high as the unannealed electrode. For the purpose of comparison, we have also plotted the data for glassy carbon on Figure 8.
To summarize the above, in 0.1 M KOH Ag(pc), Ag-Hg(pc) and Pt-Hg(pc) exhibit much lower selectivity towards H₂O₂ production and higher activity to H₂O production, relative to 0.1 M HClO₄. Glassy carbon shows far higher activity in 0.1 M KOH, relative to 0.1 M HClO₄ without compromising on the selectivity. All these catalysts sit on the weak binding side of the volcano, as shown in Figure 9; in acid, the overpotential would be limited by *OOH formation, equation 7. Our observations are in agreement with other reports on weak binding catalysts, such as those based

**Figure 14.** Oxygen reduction on (a), (b) GC and (c), (d) annealed GC using a rotating ring-disk electrode. (a), (c) Measurement in 0.1 M HClO₄. (b), (d) Measurement in 0.1 M KOH. All data taken at 50 mV/s and 1600 rpm at room temperature. Original data.
Several authors have suggested that in base, the first step proceeds via a pH-independent outer sphere mechanism involving the superoxide anion: \( \text{O}_2 + e^- \rightarrow \text{O}_2^- \). Such a mechanism could allow weak binding catalysts to circumvent the *OOH formation step at sufficiently high pH, explaining the higher activity. Even so, a very recent study from our laboratory suggests that such a mechanism may not be operative around the peak of the oxygen reduction volcano, not even for Au (100). Moreover, this superoxide-mediated pathway does not provide a trivial explanation to account for the poorer selectivity of these catalysts towards H.O production. As we discussed earlier, in acid, these catalysts show high selectivity to H.O., even though there is a thermodynamic driving force towards producing H.O. We propose that in base, the kinetic barriers preventing *H.O. or *OOH dissociation are lower than in acid. As such, only the weakest binding catalysts, based on carbon (see Figure 9a), are able to preserve the O-O bond. The fundamental reason for this difference between acid and base is challenging to elucidate using current experimental and theoretical methods; however, on the basis of recent experiments on H. evolution, we anticipate that it may be associated with the pH-dependent reorganization of the electrochemical double layer.

From a technological perspective, it is striking that a non-toxic, inexpensive and abundant material based on carbon can catalyse H.O. production so well in base. Indeed, Figure 8a suggests there is negligible room for improvement upon the activity and selectivity of annealed GC. As such, it could be tempting to replace the proton-conducting PEM electrolyte shown in Figure 6d with an anion exchange membrane (AEM). However, at present, such membranes do not constitute a mature technology: there is no commercially competitive AEM with sufficient stability and conductivity. Moreover, the HO\(_2\) anions may crossover from the cathode to anode in AEM, and be oxidized. Finally, we highlight that H.O. is less stable in base, especially at pH > 9.
Consequently, we encourage researchers aiming to improve H\textsubscript{2}O\textsubscript{2} catalysis to focus their efforts on acid solutions, more specifically on the PEM electrolyser type set-up shown in Figure 6d.

6. MESOSCOPIC EFFECTS: Mass transport of product H\textsubscript{2}O.

In the above discussion, we have thus far focused on microscopic effects that influence H\textsubscript{2}O\textsubscript{2} production. However, it turns out that mesoscopic effects related to H\textsubscript{2}O\textsubscript{2} are just as important in controlling selectivity. For instance, Pt is largely selective to the 4-electron pathway at potentials positive of 0.6 V RHE. However, at negative potentials, particularly when the surface is covered with *H, it shows increasing selectivity towards H\textsubscript{2}O\textsubscript{2}. The selectivity is not only dependent on surface structure,\textsuperscript{150} but also on the transport of H\textsubscript{2}O\textsubscript{2} away from the surface. Thus, on Pt, the Faradaic efficiency towards H\textsubscript{2}O\textsubscript{2} increases under (i) conditions of forced convection, (ii) if the catalyst loading is low, or (iii) if microelectrodes are used.\textsuperscript{151,152} Essentially, the extent to which H\textsubscript{2}O\textsubscript{2} gets reduced further to H\textsubscript{2}O (c.f. equations (11) and (12)) is a function of its local concentration at the electrode surface. Under conditions of accelerated mass transport, H\textsubscript{2}O\textsubscript{2} will move towards the bulk of the solution. Under conditions of poor mass transport, H\textsubscript{2}O\textsubscript{2} will have a higher residence time in the vicinity of the electrode, hence increasing the probability that it re-adsorbs and is converted to H\textsubscript{2}O. There are reports of similar mesoscopic phenomena on other catalysts, aside from Pt, in particular Fe-N/C.\textsuperscript{153} Most of the data we have presented in previous sections are based on RRDE experiments. However, we question whether such conditions are relevant in simulating real devices. To this end, in the current section, we present original data where we compare the Faradaic efficiencies of different catalysts in (i) a RRDE setup, (ii) a three electrodes set-up in 0.1 M HClO\textsubscript{4}, and (iii) membrane electrode assembly (MEA) set-up. The mass transport characteristics of each system will be completely distinct.
For the RRDE measurements (Figure 15a), we drop casted thin films of C-supported metal...
nanoparticle catalysts Pt-Hg/C, Ag/C, and Au/C. We also drop-casted these supported catalysts onto gas diffusion electrodes (GDEs), which were submerged in O₂-saturated 0.1 M HClO₄ solution without external forced convection, other than O₂ bubbling (Figure 15b). The same GDEs were also tested in MEA single cell set-ups (Figure 15c), which are submerged in pure H₂O, hence representative of real devices.

Figure 15d shows the outcome of our experiments. Au/C, which is 89 % selective in RRDEs, only shows around 20 % Faradaic efficiency in the GDE submerged in 0.1 M HClO₄ and the MEA measurements. Ag shows high Faradaic efficiency levels of 60-75 % in RRDE and the GDE submerged in 0.1 M HClO₄; in the MEA it shows 30 % Faradaic efficiency. Strikingly, Pt-Hg shows 90 % Faradaic efficiency in RRDE measurements, 20% in the GDE submerged in 0.1 M HClO₄, and negligible efficiency in the MEA. The selectivity obtained in the MEA is much lower than in RRDE measurements; the GDE submerged in 0.1 M HClO₄ is intermediate between the two other measurements, albeit closer to the MEA.

We attribute the differences between these measurements to the ease at which H₂O₂ is transported away from the catalyst surface. In the RRDE, H₂O₂ produced at the disk electrode is rapidly transported away from the disk electrode and oxidized at the ring electrode (Figure 15a), leading to low steady-state surface H₂O₂ concentrations. In the case of the MEA, protons will only be able to access the catalyst closest to the membrane, meaning that a large part of the H₂O₂ will be produced there; the H₂O₂ would then have to diffuse through the catalyst layer and the gas diffusion layer before it can go into the output water stream. We anticipate that the local concentration of H₂O₂ could be quite high close to the membrane; under such conditions, the kinetics of H₂O₂ reduction or chemical decomposition would be enhanced. Any solution-phase or electrode-bound impurities, as well as electrically isolated catalyst nanoparticles, would also catalyze the further
reaction of the H₂O. The situation is highly analogous to the direct synthesis process, as described in Section 2. In the case of the GDE submerged in 0.1 M HClO₄, a larger proportion of the catalyst would be accessible to protons than in the MEA; moreover, the H₂O would not have to diffuse as far before it reaches the surrounding liquid electrolyte. As a consequence, in a MEA, mesoscopic transport effects prevent Pt-Hg from yielding the high activity and selectivity exhibited in an RRDE.

We must emphasize that the data we present here on the GDE in 0.1 M HClO₄ and the MEA are not completely optimized. The RRDE measurements are far easier to control; hence we consider that they provide an upper limit to the Faradaic efficiency. Further engineering of the catalyst layer in a MEA could yield higher selectivity. Even so, it is important to acknowledge that superior performance in an RRDE does not necessarily lead to superior performance in a real device. Therefore, we advocate that researchers investigate H₂O production under conditions more representative of real devices, using either MEAs or submerged GDEs in 0.1 M HClO₄. To this end, we are currently investigating the catalysis of H₂O production on high surface area carbon materials in submerged GDEs. However, our work on Hg-based alloys demonstrates that it is possible to achieve an unprecedented combination of activity, stability and selectivity. We anticipate that further research advances will eventually lead to a catalyst that works as well as Pd-Hg in a real device, albeit without using Hg or precious metals.

7. SUMMARY AND OUTLOOK

We have elucidated the factors that control the catalysis of electrochemical H₂O production. The surface electronic structure of the catalyst surface control the activity and the selectivity by tuning adsorption energy of the reaction intermediates. Weaker adsorption of the reaction intermediates
provides higher H$_2$O$_2$ selectivity but decreases the overall activity. The geometric arrangement of surface atoms can also tune the selectivity. Isolated reactive atoms are less able to dissociate O-O bond than a contiguous ensemble of two or more atoms. The new theoretical calculations we include in this Perspective show that monoatomic sites yield a more optimal scaling relation between adsorbed oxygen and superhydroxyl; this phenomenon explains why they yield a better compromise between activity and stability.

Aside from the surface, the electrolyte composition, in particular the pH, controls the activity and selectivity towards H$_2$O$_2$ production. In rotating ring disk electrode (RRDE) measurements, all the catalysts we tested showed higher activity for O$_2$ reduction in 0.1 M KOH than 0.1 M HClO$_4$; however, with the exception of glassy carbon, they were also less selective. Glassy carbon annealed in O$_2$ was particularly active and selective in 0.1 M KOH. Even so, we recommend that researchers focus their efforts on catalyzing H$_2$O$_2$ production under acid conditions: proton conducting polymeric membranes are far more technologically mature than their hydroxide-conducting counterparts.$^{136}$

Mesoscopic effects related to mass transport are also critical in determining H$_2$O$_2$ selectivity. It turns out that RRDE measurements provide an upper boundary to the Faradaic efficiency to H$_2$O$_2$, while real devices tend to underperform. Such phenomena call for model experiments to more accurately represent the conditions of real devices.

Not only should catalyst activity be maintained over the device lifetime, but also selectivity (Section 3.1). However, several catalysts with promising beginning-of-life performance, such as porphyrins,$^{86,87}$ degrade over time. Our current insight in this area is rather limited. Future research should elucidate the mechanisms by which catalyst degradation occurs and develop strategies to prevent it from taking place.
In summary, hydrogen peroxide is a versatile and non-toxic commodity chemical. Environmental concerns and the consequent legislation are set to increase the demand for H.O, over the coming years. In particular, we emphasize that most applications require the H.O. to be produced into an effluent of pure water. The decentralized electrochemical production of H.O. is especially attractive for this purpose.

More generally, the electrochemical production of H.O. constitutes a pertinent example of a broader trend. We anticipate that the increased uptake and decreased cost of renewable electricity are set to transform the chemicals industry. We will soon be bestowed with a surplus of electrons, available for use as a key reactant for the decentralized synthesis of our most commonly used chemicals. The phenomena described herein are applicable to a broad range of electrochemical reactions of critical importance to industry, society and the environment. These include the partial electrooxidation of hydrocarbons to oxygenates, electro-carbonylation reactions and dinitrogen electroreduction to ammonia.
ASSOCIATED CONTENT

Supporting Information. Experimental and theoretical details are supplied as Supporting Information.

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Author Contributions

SY, AVC and IELS conceived and designed the experiments; AVC and SY performed the experiments. LS, LA and JR conceived the theoretical simulations; LS and LA performed the theoretical simulations. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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CONFLICT OF INTEREST DISCLOSURE

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REFERENCES


(16) Brandt, A. 20 years ago today, Helena shook, rattled and froze
http://helenair.com/news/local/article_8984de1d-0792-5aad-8021-fba2af1f35f1.html

(17) M25 chaos after lorry explosion


(31) Chinta, S.; Lunsford, J. H. A Mechanistic Study of H₂O₂ and H₂O Formation from H₂ and


(39) Foller, P. C.; Bombard, R. T. Processes for the Production of Mixtures of Caustic Soda and


(61) Shi, X.; Siahrostami, S.; Li, G. L.; Zhang, Y.; Chakthranont, P.; Studt, F.; Jaramillo, T. F.;


(89) Jinnouchi, R.; Kodama, K.; Hatanaka, T.; Morimoto, Y. First Principles Based Mean Field


(117) Forti, J. C.; Rocha, R. S.; Lanza, M. R. V; Bertazzoli, R. Electrochemical Synthesis of


(161) Figueiredo, M. C.; Trieu, V.; Eiden, S.; Koper, M. T. M. Spectro-Electrochemical Examination of the Formation of Dimethyl Carbonate from CO and Methanol at Different

