



ALLOY CATALYSTS FOR CO₂ ELECTROLYSIS

Meta | vsparticle



Contents

Executive Summary	3
1. Introduction	4
2. Alloy catalysts – challenges and opportunities	6
2.1 Composition and structure of alloy catalysts	7
2.2 Common methods for producing alloy catalysts	8
2.3 Key challenges	8
3. VSParticle Technology	9
3.1 Elemental composition control and automated printing	11
3.2 Annealing process	12
3.3 Characterization and Testing	13
4. Learnings from the Meta collaboration	14
5. Results and discussion	1.5
5.1 Crystal Structure: X-ray diffraction (XRD)	15
5.2 Elemental composition: X-ray fluorescence (XRF)	16
5.3 Electrochemical Performance	17
6. The value for industry	19
7. Spearheading future research for industry	20.
8. References	22

EXECUTIVE SUMMARY

The challenge: reducing CO, emissions

The increasing anthropogenic carbon dioxide emissions (CO_2) have a huge environmental impact which is why there is a strong surge for CO_2 emission reduction.

The solution: innovative technologies for CO, utilization

Recently, CO₂ electrolysis has attracted much attention because the process can effectively mitigate CO₂ emissions and simultaneously produce high-value-added chemicals and fuels.

Key roadblocks in implementing CO₂ technologies

The catalysts play a very important role in achieving high efficiency of converting CO_2 to desired product. As one promising alternative, the alloy catalysts have demonstrated high performance in CO_2 hydrogenation. However, major bottlenecks remain in terms of selectivity, efficiency, and stability of these catalysts. A primary challenge lies in the rapid development and scalability of alloy catalysts, which are essential for meeting industrial demands. These foundational challenges have so far limited the successful development of fully effective catalysts for CO_2 conversion at scale.

Overcoming challenges with VSParticle Technology

This paper addresses this challenge by introducing VSParticle technology that offers a fast, automated, and scalable approach to synthesize a diverse range of alloy catalyst materials with various material combinations and ratio. The technology can produce high-quality, large experimental datasets – an area where conventional wet chemistry methods fall short. These datasets were used by Meta for project Open Catalyst Experiments 2024 to train AI models to predict which material combinations might be most effective for key processes and can help researchers identify the most promising candidates to take forward further development.



INTRODUCTION

Carbon dioxide $(CO_2)^1$ is the most prevalent greenhouse gas in the atmosphere. Global energy-related annual CO_2 emissions reached a new record high of 37.4 Gt in 2023 [1]. This annual increase is 1.3% compared to the CO_2 levels in 2022. This increasing level of CO_2 emissions is causing global average temperature to increase on a yearly basis, reaching a record of 1.3°C above pre-industrial levels in 2023 [2] alerting its imminent reduction to fight climate change. To address this misbalance, new ways are being explored to revalorize CO_2 from an undesired

environmental burden into valuable products, decreasing our dependence of extraction of fossil fuels from underground.

CO₂ electrolysis has emerged as a mechanism which converts CO₂ into valuable products using electricity. **[3]** This technology not only offers a way to mitigate GHG emissions but also presents an opportunity to integrate renewable energy sources into the production of essential fuels and chemicals, establishing a circular carbon economy.

¹ For an in-depth understanding of the core principles of CO_2 electrolysis, the valuable products it can generate, and the major challenges hindering its progress, explore the insights shared in the VSParticle blog 'Advancing CO_2 electrolysis with VSParticle technology'

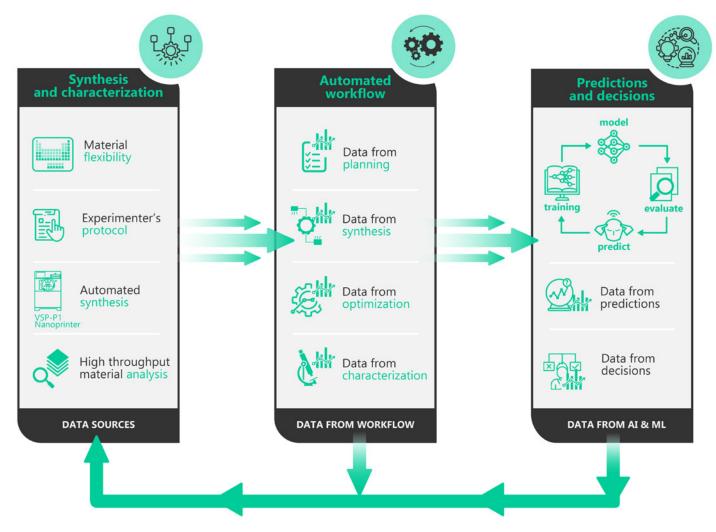


figure 1: Data-centric architecture for Self Driving Labs (SDLS)²

CO₂ electrolysis has seen slow progress over the past few decades, despite its potential to transform carbon emissions into valuable chemicals and fuels. The primary challenge has been the development of efficient, durable catalysts capable of operating at a commercial scale. While research has advanced, no commercial catalyst has yet made it to the market, leaving this promising technology underdeveloped. [4] To exploit the full potential of CO₂ electrolysis, a massive acceleration in innovation and scaling is urgently needed.

Alloying is one such innovation and a key strategy for enhancing the catalytic properties of metallic materials, resulting in a wide range of innovative alloy catalysts. However, traditional methods for producing these catalysts face significant limitations, necessitating new techniques for more efficient and tailored catalyst development. This paper addresses these challenges using VSParticle technology, providing guidelines for designing functional catalysts for specific reactions and backing them up with case studies.

Additionally, the discovery of inorganic materials has been hampered by a costly and time-consuming trial-and-error approach, unlike organic materials. While deep-learning models show promise in predicting outcomes, a large dataset for inorganic materials is crucial to speed up their discovery and practical use. VSParticle technology addresses this need by enabling rapid, scalable, and precise synthesis of advanced nanoscale materials (figure 1). This approach not only generates valuable data for AI models to predict optimal materials but also facilitates the swift transition from research to industrial-scale production, closing the gap between discovery and deployment in real-world applications.

²To learn how VSParticle technology offers a robust foundation for future SDLs, read VSParticle blog Self-Driving Labs transforming material research



ALLOY CATALYSTS: challenges and opportunities

The global catalyst market is experiencing rapid growth, driven by the increasing demand for efficient and sustainable solutions across energy production, chemical manufacturing, and environmental applications. The nanocatalysts segment, in particular, has seen remarkable expansion, with the market size reaching USD 2.58 billion in 2023. It is projected to grow to USD 4.74 billion by 2032, achieving a compound annual growth rate (CAGR) of 6.9% during this period. **[5]**

This growth reflects the growing recognition of nanotechnology's transformative potential in catalysis. Nanocatalysts stand out due to their unique physicochemical properties, which result from their nanoscale dimensions.

[6] These properties provide a high surface area to volume ratio, leading to significantly enhanced catalytic activity and reactivity compared to traditional catalysts.

2.1 Composition and structure of alloy catalysts

Alloy catalysts consist of two or more metallic elements that have been combined at the atomic level to form a single material with improved catalytic properties. The alloying process enhances the catalyst's activity, selectivity, and stability, making it suitable for CO₂ electrolysis. [3]

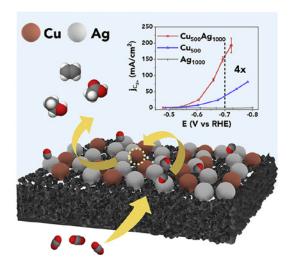
At such small scales, the electronic properties of the metals change, enabling new bonding possibilities. These nano-alloys can potentially fuse in a single phase, where metal atoms for example A, B, and C combine uniformly to form a single, stable structure (ABC), rather than forming separate phases or only partial combinations like AB and C.

Creating a stable alloy catalyst by combining metals that are typically immiscible, such as copper (Cu) and silver (Ag), can be achieved through quantum effects when the particles are reduced to nanoscale dimensions. [7] This phenomenon occurs because, at the quantum scale, the energy barriers that typically prevent Cu and Ag from mixing are reduced, making them highly active and capable of forming new types of bonds. Quantum confinement effects make the atoms "malleable" enough to overcome their

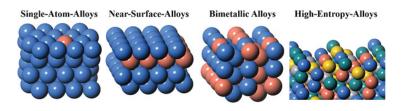
natural immiscibility, allowing the formation of an alloy structure with novel catalytic properties that are otherwise unattainable at larger scales. The structure of alloy catalysts can be finetuned based on their intended use. For instance, nanoporous alloy catalysts—in which the metal atoms form a porous structure—offer a large surface area that increases the number of active sites where reactions can occur. This structural advantage enables more efficient catalysis, making nanoporous alloys particularly valuable for carbon dioxide reduction (CO₂RR). [8] The unique advantage of alloying lies in combining the properties of different elements to achieve superior catalytic performance. However, designing alloy catalysts is challenging as it requires fine-tuning their activity, selectivity, and stability. [9] Depending on their structure and composition, alloys come in different forms:

alloys (HEAs)3 (figure 2). The discovery of new alloy catalysts is still in its infancy, largely limited by the complexity of alloy properties and the time-consuming nature of traditional experimental methods.

single-atom alloys (SAAs), near-surface alloys (NSAs), bimetallic alloys, and **high-entropy**



- **◄ figure 2:** scheme of the Cu-Ag tandem platform for high-rate CO₃ electrolysis and C₂₊ products formation. (Adapted from ref [7])
- ▼ figure 3: SAAs enhance catalysis by dispersing active atoms on a host surface, while NSAs modify surface chemical properties using secondary elements. Bimetallic alloys offer greater complexity with diverse combinations and structural variations, whereas HEAs mix multiple elements, present a promising platform for catalysts with multiple active sites.



³ To know more about HEAs, read VSParticle blog Sparking innovation | High-Entropy Alloys in electrocatalyst optimization (vsparticle.com)

2.2 Common methods for producing alloy catalysts

A critical component of advanced catalyst research is the ability to synthesize alloy mixtures—particularly in nanoparticle form—with precise control over their ratio and loading. This control is essential to minimize the influence of structural effects like thickness, porosity, and inhomogeneity on the local reaction environment. The synthesis of alloy nanoparticles can be categorized into two main approaches: "wet" and "dry" techniques. Wet methods involve a three-step process of synthesis, ink formation, and coating under ambient conditions, while dry methods typically consist of two steps involving ionization or vaporization followed by immobilization on a substrate under high vacuum conditions.

Wet methods

present challenges, including multi-steps procedures that require careful monitoring and optimization, leading to time consuming batch operations. They also necessitate complex laboratory equipment (such as Schlenk lines) and additional drying steps for hazardous chemicals, increasing both costs and potential environmental impact. Furthermore, wet methods are heavily dependent on the chemistry of the materials involved, as nature ultimately determines whether molecules react, which can introduce variability and complexity. This reliance on chemical reactions makes the process less flexible and harder to scale efficiently.

Dry methods

offer advantages, as fewer steps mean reduced optimization requirements and waste production. However, the need for high vacuum conditions can make these methods difficult to scale and automate. Additionally, films produced under vacuum conditions tend to be dense, limiting gas and liquid access and thus reducing the number of catalytic sites available in the material.

2.3 Key challenges

The industry faces significant challenges in alloy catalyst formation and selection, both of which directly influence the effectiveness of CO₂ electrolysis. Selecting and forming catalysts with optimal compositions is complex, as minor variations can alter performance, affecting the type and yield of valuable products like fuels or chemicals. Additionally, achieving high selectivity for targeted outputs remains a critical hurdle, as most catalysts tend to produce a range of products rather than a single desired chemical. Scaling up the development of these materials for industrial applications also demands rapid iteration, making it difficult to adapt material formulations to commercial scales quickly.

A key challenge is that catalyst behaviours observed in fundamental research may shift at industrially relevant conditions (IRCs), necessitating more efficient pathways to bridge labscale discoveries with real-world performance. [10] To address this, the industry requires fast, automated systems that integrate synthesis, nanoprinting, and IRC testing with machine learning-driven analysis. This approach accelerates the discovery and optimization of high-performance catalysts tailored for CO₂ electrolysis at industrial scales.



VSPARTICLE TECHNOLOGY

Spark ablation coupled with additive nanoprinting offers a promising alternative. This dry method uses only electrical energy and inert gas to convert metal rods into nanoparticle films. The process involves creating high-voltage sparks between two closely spaced metal

or alloy rods, generating a localized plasma that vaporizes material from the rods. The vaporized material then cools and condenses into nanoparticles, which can be synthesized and printed in a combinatorial manner on substrate using nanoprinter4.

⁴ Read VSParticle blog 'Spark Ablation for Nanoporous Production' to learn about how VSP-P1 operates.

The VSParticle nanoprinting system offers a range of advanced capabilities that make it ideal for cutting-edge catalyst research and development. This unique technology is:

Material and substrate agnostic:

VSParticle's technology stands out for its material and substrate agnostic approach, capable of processing a broad range of elements—approximately two-thirds of the periodic table—with minimal adjustments. Unlike chemistry-based methods, which require unique synthesis recipes for each material, VSParticle's spark ablation method uses the same device setup to produce a variety of nanoporous layers across different substrates, like silicon wafers and gas diffusion electrodes (GDEs), without relying on specific material compatibility.

Most advanced nanoporous layers:

The technique enables the production of the smallest stable nanoparticles, which are crucial for fabricating advanced thin-film nanoporous layers. This high level of precision places spark ablation ahead of other technologies, allowing for the development of cutting-edge materials with superior properties.

Combinatorial printing capability:

By controlling the composition and structure of printed layers, VSParticle technology allows for the rapid creation and testing of diverse material combinations, accelerating the discovery of optimal catalysts.

Scalable for large-scale production:

The technology's automated and precise layer-by-layer building process ensures reproducibility and consistency, enabling scale-up potential for industrial applications.

3.1 Elemental composition control and automated printing

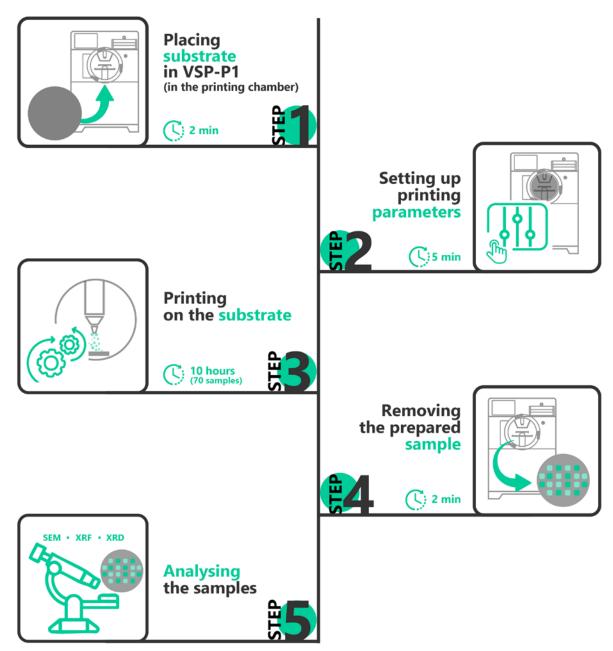


figure 4: Automated steps in printing nanoporous layers

The VSParticle nanoprinting system offers a significant advantage in its capacity to control elemental composition and structural characteristics in the printing process, making it ideal for advanced catalyst development. Using multiple nanoparticle generators, researchers can swiftly produce a diverse array of material compositions, making it especially valuable for combinatorial material discovery. This approach facilitates the rapid screening of large datasets to identify the most promising catalyst candidates for specific application.

The standard VSP-P1 system can work with two VSP-G1 nanoparticle sources. Both sources produce nanoparticles that combine into a single gas stream, which is then directed through the printer nozzle. Furthermore, the system's compatibility with **70 elements** from the periodic table enables the fabrication of complex nanoporous alloy films, offering a broad range of material options tailored to specific applications⁵. For this study, 348 diverse materials were synthesized from 13 different elements (figure 4).

⁵ VSP-P1 compatible with 70 elements Nanoparticle database

For example, if one source uses gold electrodes and the other uses copper electrodes, the VSP-P1 will produce a nanoporous layer made up of a mix of gold and copper nanoparticles. The ratio of gold to copper in the printed layer can be adjusted by changing the power settings on one of the VSP-G1 sources while keeping the other at maximum power. Reducing the output is done by lowering the current while keeping the voltage steady. The thickness of the printed layer is controlled by adjusting how fast the printer's stage moves during the process. The system is capable of simultaneously printing catalyst layers on Si-wafer and Gas Diffusion Electrode (GDE) as substrates, allowing for efficient batch processing. This synthesis can be

performed as an overnight protocol, it sequentially prints a layer on the Si-wafer followed by the layer on GDE, ensuring consistent application across both. The process can also be further refined through custom scripts, allowing incremental layer-building (e.g., 1/5 of the Si-wafer followed by 1/5 of the GDE, then the next layers, and so on), thereby providing a high degree of freedom in layer-building (figure 5). This strategic flexibility enhances reproducibility and uniformity across samples, yielding consistent catalytic layers across various substrates. The result is a substrate-independent coating protocol that can be applied across platforms, supporting versatile and scalable testing and analysis.



figure 5: Changing elemental composition on the fly

3.2 Annealing process

After nanoprinting of mixed materials, heat treatment at mild temperatures is applied to alter the internal atomic arrangement, enhancing the material properties. The small size of the nanoparticles allows for rapid alloying during the annealing process while maintaining the nanoporous structure. As the temperature increases, the particle size gradually grows, eventually forming a solid layer. By carefully optimizing the annealing temperature, it is possible to form alloys without significantly compromising

porosity. These changes in the microstructure can impact various properties, including electrochemical and mechanical performance. The structural changes are tracked via X-ray diffraction (XRD), which confirms the formation of alloy phases. Despite some sintering of nanoparticles during the heat treatment, the materials retain their critical nanoporous architecture, which ensures a high number of active catalytic sites.

3.3 Characterization and Testing

The search for a catalyst that surpasses copper in generating multi-carbon products in CO₂ reduction reactions (CO₂RR) remains a key research challenge. Although copper demonstrates a notable ability to form multi-carbon compounds, enhancing its activity, selectivity, and stability is crucial for advancing CO₂RR processes. For each material studied, compositional analysis through X-ray fluorescence (XRF) and

structural characterization via X-ray diffraction (XRD) were performed to confirm purity and elucidate crystalline structure. Electrochemical CO₂RR testing is subsequently conducted at current densities relevant to industrial applications, focusing on single-phase samples with well-defined structural conformity to target compositions, as validated by XRD (figure 6).

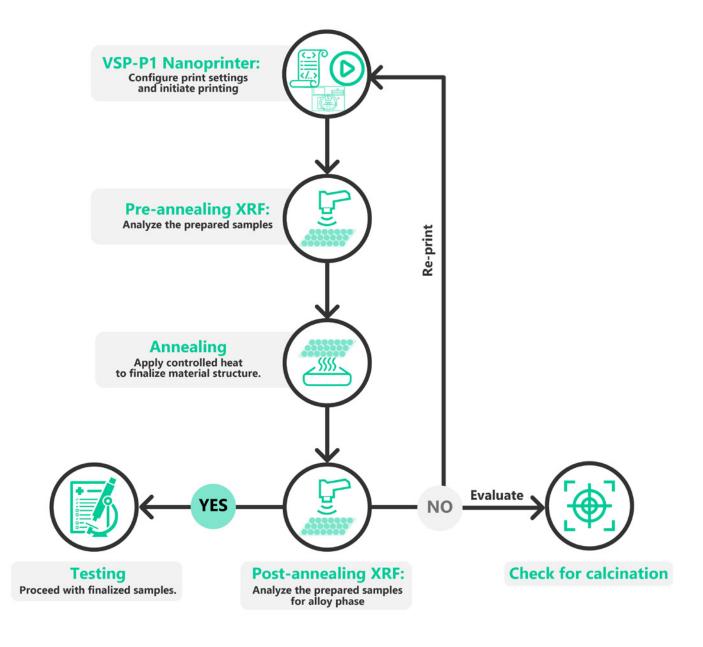


figure 6: Experiment workflow

LEARNINGS FROM THE META COLLABORATION

Through the Meta collaboration, the capabilities of VSP technology in producing advanced catalyst materials have been further validated. Some of the key insights from this partnership include:

Alloy formation and porosity retention:

Using dual nanoparticle sources, VSP demonstrated the successful formation of alloys after annealing. For example, combining gold and copper electrodes resulted in a nanoporous alloy that maintained its structural integrity and porosity post-annealing. This is crucial, as porosity enhances the accessibility of catalytic sites.

Proof of optimal technology for Self-Driving Labs (SDL):

VSP technology demonstrated precision in elemental control and uniform layer deposition, solidifying its position as an optimal platform for SDLs. This high-precision deposition is ideal for experimental setups requiring exact control over nanoparticle size and composition.

Demonstrated activity for CO₂RR:

VSP-produced materials exhibit significant catalytic activity for CO₂ electroreduction, highlighting their potential to contribute to sustainable energy solutions.

VSP's innovative approach provides the automation and speed necessary for creating nanoporous materials at scale. While other technologies would require decades to synthesize the volume of materials achieved in this project, VSP enabled the rapid creation of a vast number of potential catalysts, making the collaboration possible. The findings were incorporated into an experimental database, allowing researchers to validate AI-driven predictions with real-world

outcomes. This database enabled the identification of hundreds of potential low-cost catalysts for key reactions and now serves as a foundation for further training and refinement of AI and machine learning models. In total, the project ran a record-setting 20 million simulations, the largest computation of its kind, which will support even larger databases and accelerate the scaling of catalyst development processes.

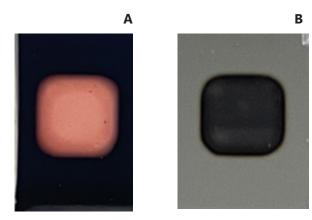
RESULTS AND DISCUSSION

5.1 Crystal Structure: X-ray diffraction (XRD)

Before initiating alloy testing, we conducted an internal benchmark of our P1 catalyst layers to ensure compatibility with the testing platform at industrially relevant current densities, using copper (Cu) as a reference material. The results closely aligned with established literature, confirming stability under these conditions (Figure 7). This benchmark was essential due to the absence of any binder, additive, or ionomer in our films, necessitating verification of system stability during high-current CO₂RR. At such high currents, challenges like particle corrosion, physical integrity of the film, and substrate stability become critical, especially in preventing issues such as flooding and salt formation that could impact CO₂RR performance.

Sample of silver (Ag) and gold (Au) nanoporous thin films were analyzed using XRD (figure 8). The shifts in the XRD peaks observed before and after heating confirm the successful formation of an alloy while maintaining the desired porous structure.

The shifts in XRD peaks before and after annealing demonstrate the successful formation of alloy phases within the material, correlating directly with enhanced catalytic performance as shown by electrochemical testing.



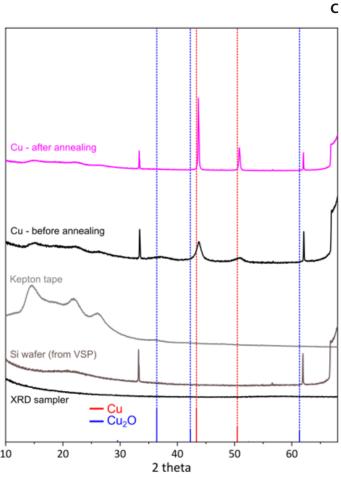


figure 7: (A) Cu layer before annealing on Silicon wafer (B) After annealing on Silicon wafer (C) XRD results showing shift in peaks.

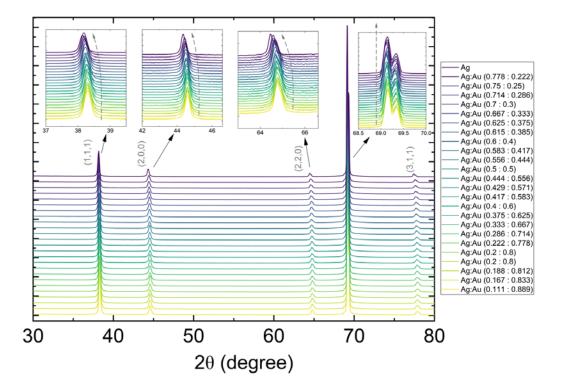


figure 8: XRD analysis of Ag-Au on Silicon wafer samples demonstrates a peak shift at the designated diffraction points for Ag and Au, indicating alloy formation. In contrast, the substrate peak at approximately 69.2 remains constant, confirming no shift in the substrate during the alloying process.

5.2 Elemental composition: X-ray fluorescence (XRF)

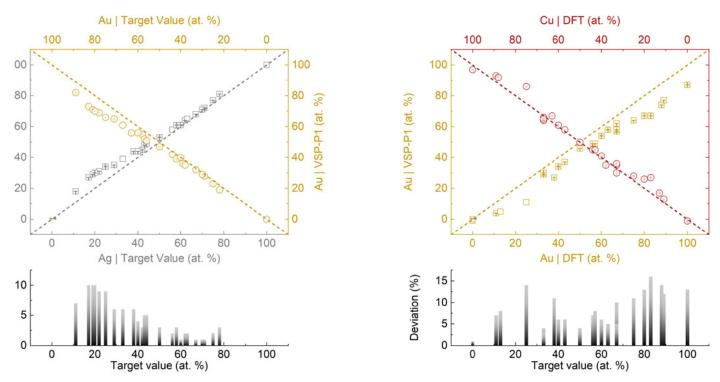


figure 9: (A) Aq-Au composition deviated ± 5% from the target composition (B) Au-Cu composition deviated from 1-15% from the target composition.

The precision of the nanoprinting process is demonstrated through the accurate reproduction of targeted alloy compositions. **Figure 9A** presents the XRF results for silver-gold (Ag-Au) alloys, where a target composition of 80% silver and 20% gold resulted in a final composition of 76% silver and 24% gold, demonstrating the process's capability to closely achieve the intended specifications. This degree of com-

positional control is essential for developing high-performance catalysts that meet specific industrial requirements. In **Figure 9B**, the XRF measurements of gold-copper (Au-Cu) alloys shows that the output of a nanoparticle source could deviate 1-15% from the target composition. There is still potential for further improvement in the ability of the device to print certain elements.

5.3 Electrochemical Performance

For industrial scale CO₂ processes, achieving high current density (CD) is essential because it directly relates to the rate of CO₂ conversion into desired products. Gas Diffusion Electrode (GDE), consisting of a gas diffusion layer (GDL), catalyst layer (CL) and current collector, improves mass transfer rates and reaction efficiencies. Optimizing GDE designs can lead to higher current densities and Faradaic efficiencies. In electrochemical testing, catalysts with low copper (Cu) loadings demonstrated significantly higher current densities compared to other

methods, indicating a superior ability to drive reactions under industrial conditions. For example, in comparison tests of Cu-based catalysts, our system achieved current densities of 300 mA/cm²—several orders of magnitude higher than conventional catalysts used in water electrolysis. This high performance is crucial for industrial scalability, especially in energy-intensive processes like hydrogen production. At 200 mA/cm², the production of C₂ products is comparable to the baseline level (figure 10).

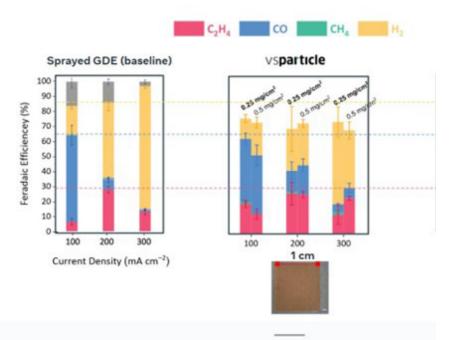


figure 11: Impact of composition on catalyst performance: In the Ag-Au sample, adjusting the composition significantly influenced selectivity at high current densities. A composition on 33% Au and 67% Ag demonstrated high selectivity for CO and H₂ with no liquid products detected under elevated current density conditions.

This approach represents a significant breakthrough in catalyst research, enabling the rapid production and optimization of novel alloy materials with high efficiency for applications such as proton exchange membrane (PEM) water electrolysis and CO₂ electrolysis, paving the way for more efficient and scalable clean energy technologies.

Given its demonstrated applicability and alignment, we proceeded with the next step of our protocol. The reproducibility and accuracy of

alloy formation facilitate the rapid development of new catalyst materials, significantly reducing the time and cost associated with conventional trial-and-error methods.

In the Ag-Au sample, adjusting the composition impacted catalyst selectivity at high current density. With a composition of 33% Au and 67% Ag, we observed a high selectivity toward CO and H₂, with no liquid products detected at elevated current density **(figure 11)**.

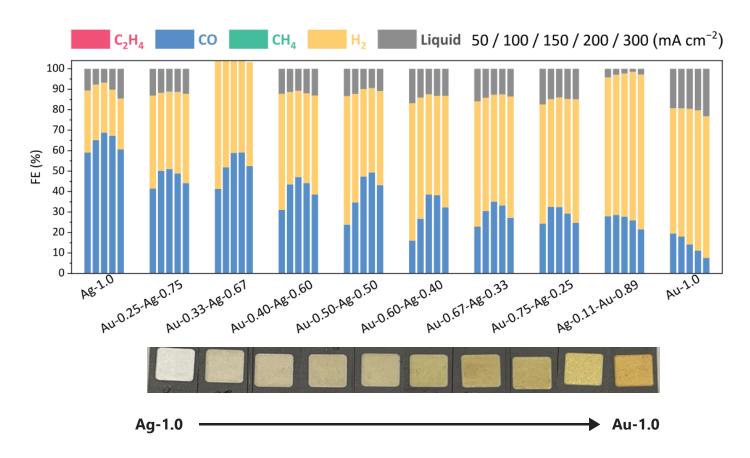


figure 11: Impact of composition on catalyst performance: In the Ag-Au sample, adjusting the composition significantly influenced selectivity at high current densities. A composition on 33% Au and 67% Ag demonstrated high selectivity for CO and H₂, with no liquid products detected under elevated current density conditions.

THE VALUE FOR INDUSTRY

Research Tool

Process Development Tool

Production Tool

Only applied Sylven Company (Sylven Company (Sylven

VSParticle is pioneering a new standard in nanoparticle production by exploiting nanotechnology and quantum properties to streamline the process to a simple push of a button. Through advanced automation and machine learning, VSParticle fully automates, scales, and digitizes material production. Currently, the VSP-P1 Nanoprinter (Research Tool) combined with the VSP-G1 nanoparticle generator provides massive, high-quality experimental datasets to work from and to build AI databases. However, when the best catalyst has been identified, this technology is not enough to meet the industrial demand of electrolyzer market.

To enable large-scale industrial applications, VSParticle is working towards Process Development Tool (PDT), equipped with the next-generation VSP-G100 Nanoparticle Generator. This new tool is designed to increase mass output by 100x compared to the VSP-G1. This boost in production capacity will be accomplished by increasing the electrical sparks frequency that

generates a certain number of nanoparticles. With a target of 25,000 sparks per second, the PDT is set to reach a printing speed 100x faster than current models operating at 300-500 sparks per second.

VSParticle's scaling strategy emphasizes "numbering up" individual VSP-G100 modules, providing a streamlined expansion approach that preserves nanoporous material properties across different scales. Therefore, in the next phase, VSParticle will develop a High Volume Production Tool (HVPT), incorporating at least 10 particle generators to achieve technological maturity for industrial-scale nanoporous material production.

The PDT is a critical step toward meeting future demand of GDE and demonstrates the scalability of VSParticle's approach. It sets the stage for high-volume production, with the VSP-G100 as the core technology, positioning VSParticle as a disruptive force within the electrolyzer market.



SPEARHEADING FUTURE RESEARCH FOR INDUSTRY

Our research has focused on advancing catalyst development and material synthesis for critical electrochemical processes, with a particular emphasis on overcoming the limitations of traditional methods such as the wet synthesis approach. Looking ahead, our work hints at exciting future directions in the broader field of electrolysis, including the potential application of our technology to solve long-standing industrial challenges. For instance,

Substituting Iridium in water electrolysis:

We are pursuing alternative catalysts to replace iridium in water electrolysis. This advancement would enhance both the sustainability and scalability of the process, paving the way for more accessible and cost-effective hydrogen production.

Revolutionizing fertilizer production:

One of the most impactful applications of our technology by improving the electrolysis of nitrogen gas (N2) to ammonia. The current Haber-Bosch process, which has been used for nearly a century, depends on fossil fuels and operates with low efficiency. [11] By developing an effective catalyst for nitrogen electrolysis, we could significantly reduce the environmental impact of ammonia production, making fertilizer production cleaner and more efficient

Transforming ethylene to ethylene oxide production:

Another potential avenue lies in converting ethylene to ethylene oxide via an electrolysis route. Although this concept remains in early stages, it holds transformative potential for the chemical industry. Ethylene oxide is essential in battery development for electric vehicles and supports a range of industries, including agriculture and energy. [12] If successful, this method could revolutionize the production of ethylene oxide, making it more sustainable and scalable.

Our approach offers a seamless path from R&D to material development automation, enabling the scaling up of high-performance materials for mass production at an industrial level. By streamlining catalyst synthesis and integrating machine learning-driven analysis, VSParticle is poised to lead the way in advancing CO2 electrolysis and other electrochemical processes. This progression not only accelerates the development of sustainable energy solutions but also offers significant commercial propositions for industries seeking to reduce costs, improve efficiencies, and adopt more environmentally friendly technologies.



REFERENCES

- [1] I. E. Agency, "CO₂ Emissions in 2023".
- [2] N. C. Science, "Global Temperature".
- [3] Y. Z. P. X. L. C. Jiayi Lin, " CO_2 electrolysis: Advances and challenges in electrocatalyst engineering and reactor design," Materials Reports: Energy, vol. 3, no. 2, 2023.
- [4] A. Harriman, "Electrochemical catalysts to meet the challenge for sustainable fuel production from renewable energy," Current Opinion in Green and Sustainable Chemistry, vol. 30, 2021.
- [5] B. R. insights, "Nano catalysts market report overview".
- [6] K. P. a. P. Serp, Concepts in Nanocatalysis.
- [7] K. L. B. J. W. S. W. Z. X. L. T. M. Dezhi Xu, "Electrocatalytic CO_2 reduction towards industrial applications," Carbon Energy, vol. 5, 2022.
- [8] M. M. I. N. J. A. M. K. A. T. F. S. I. M. M. L. G. C. B. R. I. W. Grandprix T.M. Kadja, "Recent advances on the nanoporous catalysts for the generation of renewable fuels," Journal of Materials Research and Technology, vol. 17, pp. 3277-3336, 2022.
- [9] W. G. Ze Yang, "Applications of Machine Learning in Alloy Catalysts: Rational Selection and Future Development of Descriptors," Advanced Science, vol. 9, 2022.
- [10] E. A. Sandra Hernandez-Aldave, "Fundamentals of Gas Diffusion Electrodes and Electrolysers for Carbon Dioxide Utilisation: Challenges and Opportunities," Catalysts, 2020.
- [11] A. K. H. a. L. T.-M. Collin Smith, "Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape," Energy & Environmental Science, vol. 13, 2020.
- [12] A. C. Council, "Ethylene Oxide Critical Building Block for the Automotive Industry," [Online].