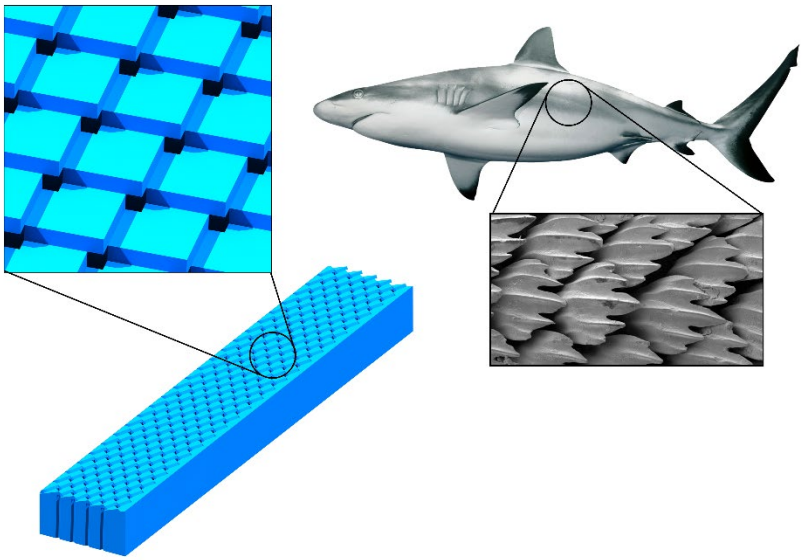
SME Digital Manufacturing Challenge 2025

Novel bio-inspired electrode design for affordable green hydrogen production



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Part 1
Executive Summary

Hydrogen, as a molecule with high energy storage capability, is a crucial element in the future of sustainable transportation, agriculture, and manufacturing. The increasing demand for green hydrogen, produced through water electrolysis using electrolyzers, as an affordable and sustainable energy carrier has highlighted the need for cost-effective and efficient electrolyzer designs. To satisfy the need, in this work, a novel bio-inspired membrane-less design has been proposed for electrodes, which are responsible for carrying out the half-reactions of water oxidation and reduction. This innovation is addressing the trade-off between productivity, efficiency, and product purity. The design incorporates innovative electrode structures, optimized for bubble extraction and flow performance, and is fabricated using additive manufacturing (AM) techniques. This innovation greatly reduces the capital cost and operational cost of electrolyzers, enhancing the scalability and accessibility of green hydrogen production.

In the proposed solution, laser powder bed fusion (LPBF), as well as binder jetting (BJ), enables the fabrication of controlled surface textures. COMSOL modeling results are presented to showcase the potential of the design in ensuring a uniform distribution of water velocity and pressure among electrodes. The material selection of stainless steel 316L ensures cost-effectiveness and electrochemical stability. The printed electrodes can be easily integrated with a modular electrolysis stack, enabling simple assembly and disassembly and ease of scaling depending on the need compared with other electrolyzers.

The proposed design strongly complies with sustainability goals, by offering a low-cost and scalable solution for green hydrogen production. By improving the affordability of green hydrogen, the design demonstrates the potential to significantly impact industries such as transportation and agriculture, providing an environmentally friendly alternative to fossil fuels.

Part 2
Industry Overview

Hydrogen is recognized as a viable alternative to fossil fuels, as it can be used as an energy storage medium and an energy carrier, facilitating the global movement to achieve zero emissions [1]. When used as fuel, whether in combustion engines or fuel cells, the only byproduct is water, making it an ideal solution for reducing carbon emissions across various applications [2]. Besides, the molecule is widely used in chemical industries and is the major ingredient of ammonia production, the root compound for making fertilizers [3]. However, the current 97 megatonnes per year capacity of hydrogen production is dominated by traditional carbon-intensive methods, with sustainable production routes having shares of less than 1% [4]. This has hindered the dream of sustainability in steel manufacturing and agriculture, both having great capabilities to reduce their emissions with green hydrogen.

What limits the widespread utilization of green hydrogen production methods is their high capital and operational costs [5, 6]. The most famous one of these techniques is electrolysis, involving passing an electrical current through water by two electrodes to break molecular bonds, producing hydrogen and oxygen through cathodic and anodic reactions, respectively. Despite numerous developments in the field, the industry still lacks the technologies needed to achieve a combination of low costs, high efficiency, high production rate, and high product purity. Current industrial-scale products include proton exchange membrane (PEM) electrolyzers, alkaline water electrolyzers (AWEs) and anion exchange membrane (AEM) electrolyzers [6]. All three systems consist of at least a cathode, an anode, and a membrane positioned between the electrodes to minimize gas cross-over. However, these membranes are costly, consumable, and require periodic replacements, while causing system losses due to high ohmic resistance [7]. In addition, as delicate organic structures, these membranes cannot withstand high temperatures and pressures, limiting the operational parameters of the system.

To address these challenges, several start-ups, primarily rooted in academia, have explored the possibility of eliminating membranes, leading to the development of membrane-less water electrolysis. This emerging class of electrolyzers relies on alternative solutions rather than the application of membranes to prevent gas cross-over [8]. Membrane-less systems can be categorized into two major subgroups: flow-by [9] and flow-through [10] systems, where the water flows past and through the electrodes, respectively. In such systems, water motion should be completely laminar to keep bubbles separated, directing them toward separate outlets for hydrogen and oxygen. Such a system not only enables higher operational temperatures and pressures but also, at least in theory, reduces ohmic losses and improves overall system efficiency [11]. However, these systems face a trade-off between productivity and efficiency on one side and product purity

on the other. A higher production rate increases the bubble fraction in the electrolyte, while a smaller inter-electrode gap greatly enhances efficiency. However, both factors dramatically increase the risk of gas cross-over. Besides, as shown in COMSOL [12] modeling results presented in Figure 1, flow-through systems, where porous media such as meshes are commonly used as electrodes, experience a significant drop in velocity and pressure of water. This reduction prevents sufficient water flow from reaching all regions, increasing the possibility of gas cross-over. Similarly, in flow-by systems, which use plates or planar coated surfaces as electrodes, bubble fraction increases with bubble accumulation along the electrode length, further increasing the chance of gas cross-over. Therefore, to minimize gas impurities in both cases, it is recommended to reduce electrode size while maximizing the gap between them.

Therefore, an optimal solution should be developed to enhance bubble extraction efficiency – reducing the risk of gas contamination, while enabling the use of larger electrodes to increase productivity and minimum gap size to improve efficiency, via design optimization. Such an innovative design would make electrolysis more affordable, especially in low-income countries, by reducing both operational and capital costs.

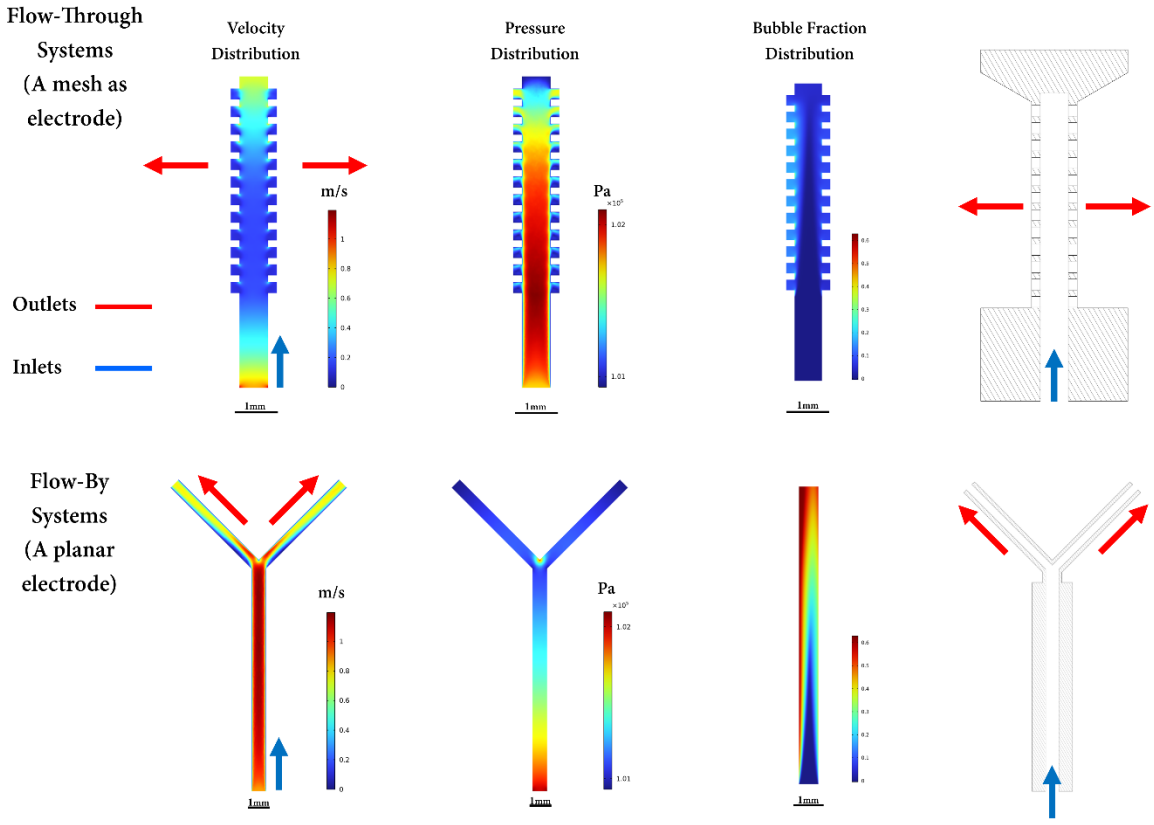

Figure 1: COMSOL modeling results for flow-through and flow-by membrane-less electrolysis systems, showing the velocity, pressure and bubble fraction distribution along the channels in-between the electrodes.

Part 3
Design, Functionality and Durability

An optimal electrode design should be a combination of flow-by and flow-through systems, as illustrated in Figure 2. In other words, instead of relying on either a highly porous electrode or a simple plate where water passes by to collect the bubbles, we can design an electrode with localized plates that generate gas bubbles, and adjacent pores that allow the water-bubble mixture to be extracted. Therefore, the flat-to-pore ratio of the optimal design should fall between that of a flow-by and flow-through system. This design ensures that bubbles are extracted near their production site, preventing gas mixing. As a result, extraction efficiency will match that of flow-through systems, while velocity and pressure distribution will resemble that of flow-by systems. In such a system, following parameters need to be optimized:

1. Size of the plates: As the plates increase in size, the productive area increases, thus, water must collect more bubbles before reaching an extraction pore. Therefore, it is important to determine the maximum distance at which bubbles remain separated and can be effectively extracted. The simulation shown in Figure 1 indicates that in flow-by systems, where two electrode plates face each other, the bubble fraction remains well below 5% along the centerline between the electrodes within the first 5 mm. This suggests that each plate should have an extraction point at a maximum distance of 5 mm, which is in accordance with the findings reported by Pang et al. [13].
2. Size and number of pores: As the pore size increases, a higher amount of water can flow through each pore, leading to less water available for the later pores along the electrode. On the other hand, ultra-fine pores may cause excessive pressure drops, pose challenges in bubble and water motion in the pores, and create manufacturability issues. Therefore, an optimal pore size should be determined, which is in the range of 50 to 100 microns. Besides, instead of a linear outlet along the electrode height, discrete radial pores or outlets allow the water to be used more efficiently, supporting longer electrodes and enhancing overall productivity.
3. Shape of the plates: One might suggest using a single plate with small pores distributed across its surface. However, the key advantage of using additive manufacturing for producing these electrodes lies in its capability to create a controlled surface texture that facilitates efficient bubble extraction with minimal water flow. For this purpose, the surface texture should be designed to guide the bubbles toward their designated pores, enabling the use of fewer pores while maintaining larger active plate areas.
4. Inter-electrode gap: In both conventional electrolyzers and membrane-less electrolyzers, the distance between the anode and cathode is typically constant. While this arrangement is suitable

for conventional electrolyzers, it might not be the optimal option for membrane-less systems. As water enters the inter-electrode space, some of it, mixed with newly formed bubbles, escapes through the pores. Consequently, less water flows through the later sections of the electrode, which would result in a reduced water velocity at a constant inter-electrode gap. To fix this, the gap between the electrodes can gradually decrease, maintaining a constant velocity despite the decreasing flow rate.

With a design incorporating all the aforementioned features, a uniform distribution of water velocity and pressure within the inter-electrode space is expected at any given point. In addition, high product purity can be expected, as hydrogen and oxygen bubbles are immediately extracted after formation. In contrast to flow-by membrane-less systems, this approach reduces the need for maintaining a perfectly laminar water flow.

Given that the scale of the gap is sub-millimeter and the size of extraction pores should be as small as possible, typically in the range of tens of microns, additive manufacturing becomes the most viable production method, which provides great control over surface texture and roughness, while maintaining a suitable balance between production speed and cost. Surface roughness and print resolution are particularly critical, as any surface irregularities might cause unexpected bubble motion due to collisions, increasing the risk of gas mixing. Therefore, print accuracy is the primary quality consideration, as the electrodes are not subjected to mechanical or thermal loading, and their electrochemical performance depends more on material selection rather than production method. To ensure smooth bubble motion, a surface roughness (Ra) of less than 5 micron is required.

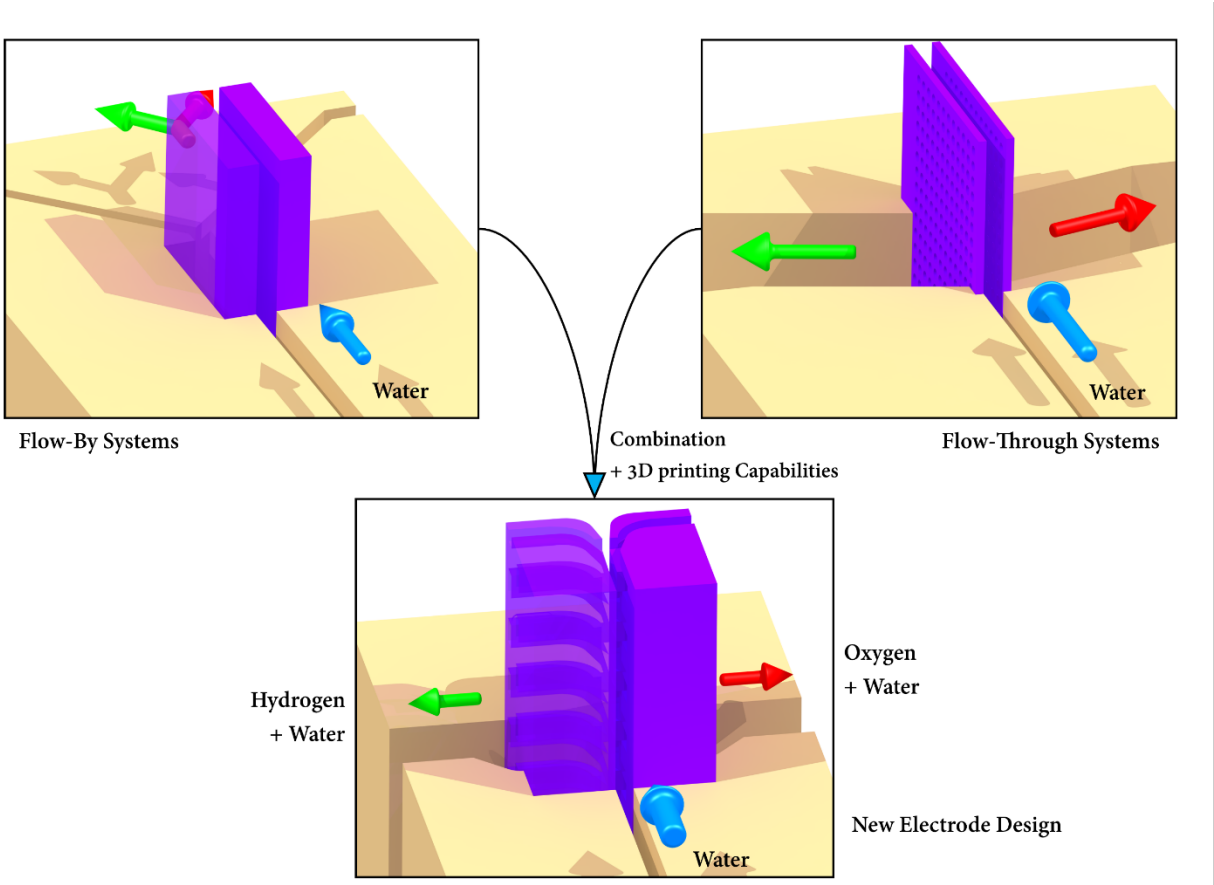

Figure 2: A schematic of the two major membrane-less techniques, flow-by and flow-through, consisting of two electrodes (either plates or meshes) that water flows by or through, respectively, along with a schematic of the newly designed system, additively manufactured with planar regions (flow-by) that feature their own extraction points (flow-through).

The ideal design is shown in Figure 3, inspired by shark skin, consisting of flake-like pieces. The top surface of each flake produces hydrogen / oxygen, while the pores at each end allow for bubble extraction. Two types of steps are observable in the design. One results from the angle of the flakes, creating guiding walls that direct bubbles to the designated pores, rather than allowing them to move to other flakes. This guidance system helps with limiting bubbles of each flake to their designated region, reducing ohmic loss due to bubble resistivity in the later sections of the electrode. The other notable feature of the design is the incremental decrease in gap size, lowering the cross-sectional area through which water flows, thus maintaining a constant velocity.

The velocity and pressure distribution of water in-between the two electrodes, obtained by COMSOL modeling and presented in Figure 3, shows a uniform pressure distribution along the electrode length, with no noticeable pressure drop. Besides, at the center of the gap, a relatively high velocity of water is maintained even at the end of the electrode. This combination of high velocity and pressure, along with a

high production rate and a small gap size (set at 0.6mm), is a remarkable achievement that has not been reported in any previous studies.

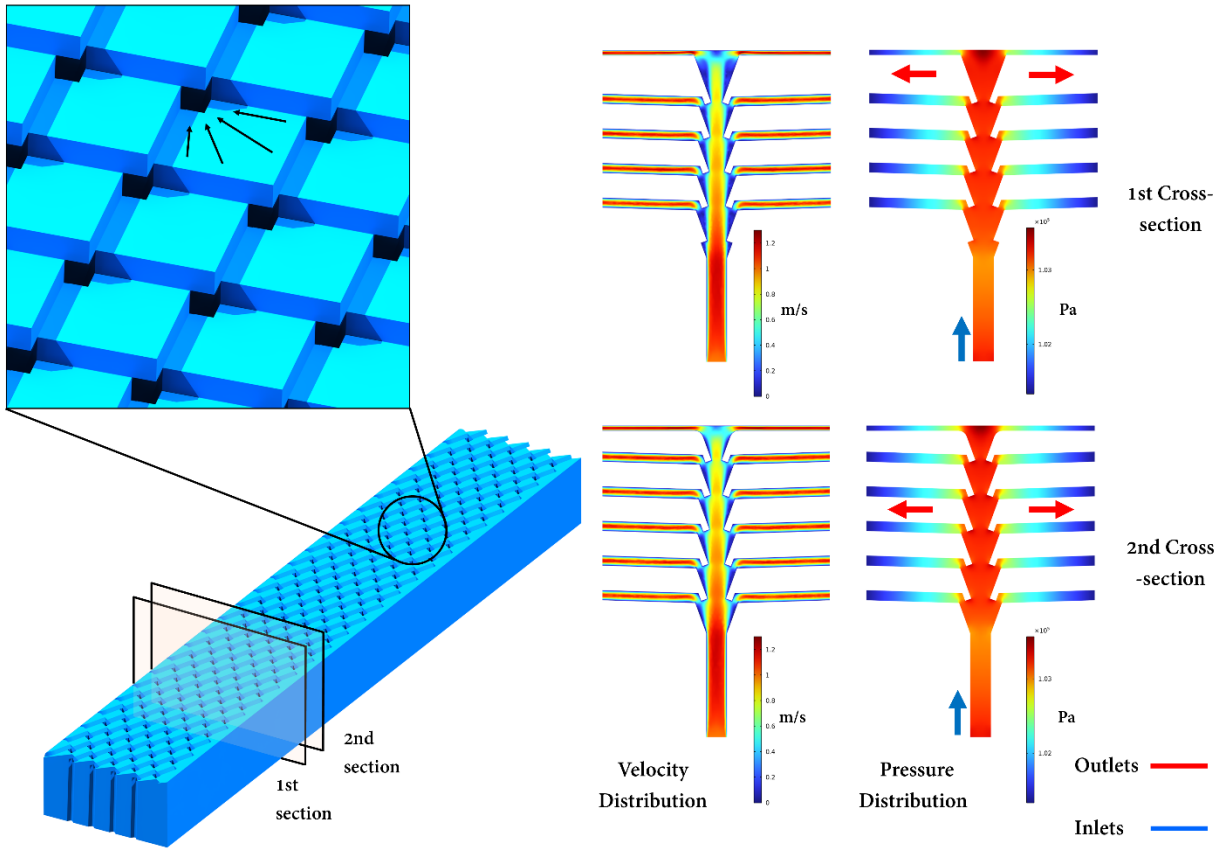

Figure 3: The novel ideal design, inspired by shark skin, comprising hundreds of flakes, each with an extraction pore at the end, with COMSOL modeling results showing velocity and pressure distribution in the gap between two electrodes with the proposed design facing each other (anodes and cathodes) in two cross-sections of the design.

The manufacturability of the parts, even for additive manufacturing, presents a challenge due to the need for high-resolution printing with ultra-fine features. Conventional laser powder bed fusion (LPBF) methods allow for the production of parts down to 100 microns [14], but when pores of this size are created, they are usually filled with partially sintered particles that block water flow. However, there are LPBF machines capable of producing ultrafine features by reducing the spot size of the laser beam as well as reducing particle size in feedstock material. They are capable of achieving features much smaller than those in our ideal design presented in Figure 3. Furthermore, considering sintering contraction, binder jetting (BJ) is a viable and more cost-effective option for producing these parts. However, since machines with required resolutions are not available in our lab, we simplified the designs to those presented in Figures 4 and 5 and printed them with Renishaw AM400 LPBF system from stainless steel 316L, to showcase our concept.

The simplified designs, despite having larger pores, still incorporate the core concepts of the ideal system, including regional extraction pores and a stepwise reduction in gap size. As a result, the two new designs demonstrate promising results in terms of pressure and velocity distribution. The water parameters remain almost consistent across all sections of the inter-electrode gap region, ensuring maximum bubble extraction efficiency.

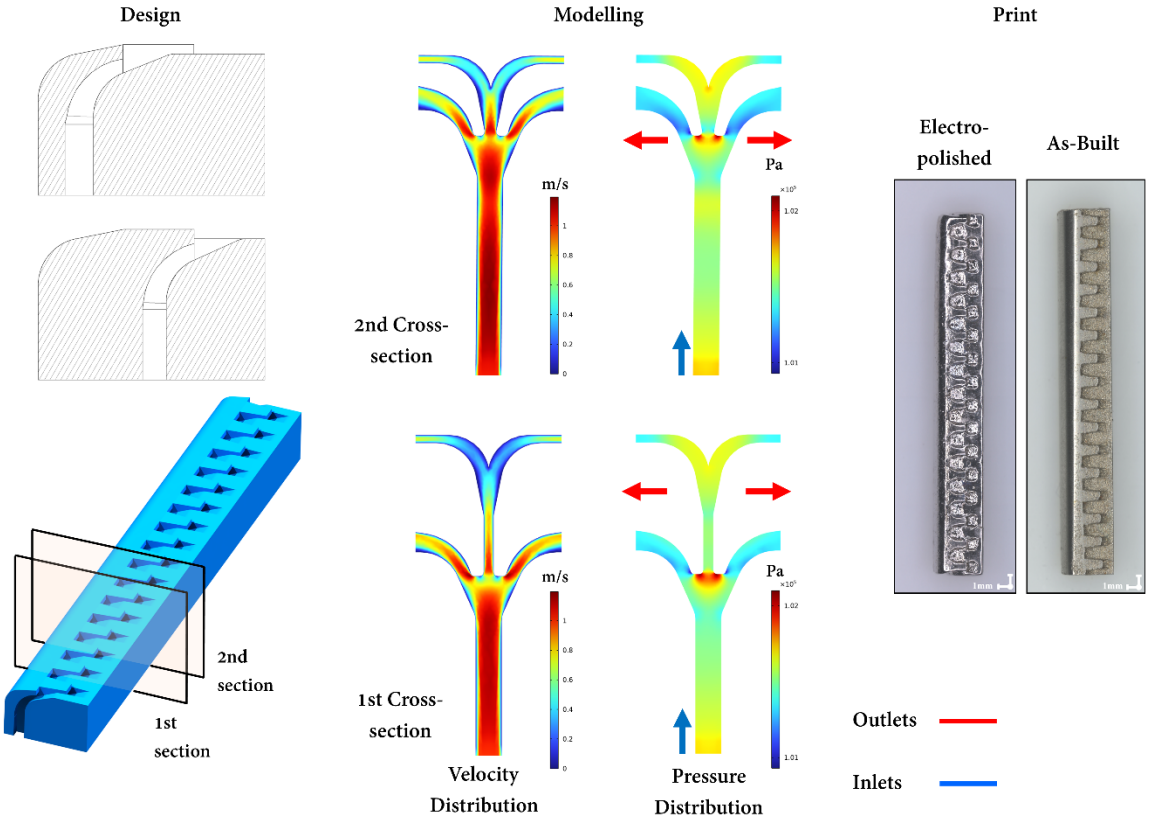

Figure 4: Simplified design #1, with fewer but larger pores, COMSOL modeling results showing velocity and pressure distribution of water along the pathway till the end of the electrode in the gap between two electrodes with the proposed design facing each other (anodes and cathodes) for two different cross-sections, and printed samples before and after electropolishing, demonstrating the feasibility of LPBF in printing the parts without parameter optimization.

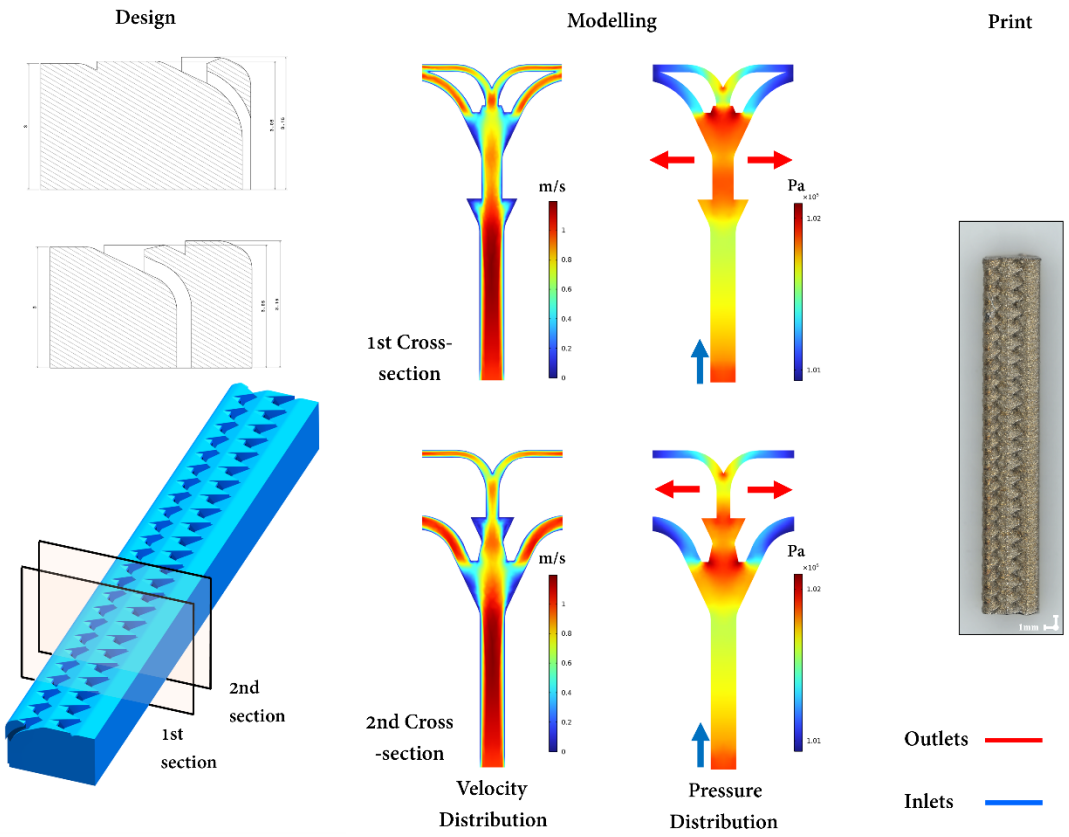

Figure 5: Simplified design #2, with fewer but larger pores, COMSOL modeling results showing velocity and pressure distribution of water along the pathway till the end of the electrode in the gap between two electrodes with the proposed design facing each other (anodes and cathodes) for two different cross-sections, and printed sample demonstrating the feasibility of LPBF in printing the parts without parameter optimization.

Part 4

Design Integration and utilization of DDM materials and processes

AM enables the production of electrodes with complex internal channels and outlet structures while providing complete control over surface texturing, which are not achievable with conventional manufacturing methods. By integrating AM with conventional post-processing techniques such as electropolishing, the electrodes can achieve the necessary surface smoothness to guide bubble extraction efficiently while minimizing gas crossover.

In conventional electrolyzers, electrodes are typically made from precious metals, such as platinum and its alloys. These materials, while effective, remain costly and are limited in design complexity. As mentioned earlier, our novel electrodes are manufactured from stainless steel 316L using a Renishaw AM400 machine. The selection of this material is based on its well-established printability, cost-effectiveness, suitability for both hydrogen (HER) and oxygen evolution reactions (OER), as well as its electrochemical stability [15]. However, as an alternative option, a conductive and stable material, such as titanium, can be used, with the top surface spray-coated with an active material, such as Pt/C, to enhance electrochemical performance. The deposition of active material can also be benefited from AM, since direct writing approaches can be used for material deposition at selected positions.

As stated before, LPBF is selected for this design due to its high resolution and ability to print complex features. The precision of LPBF ensures the accurate production of the optimized electrode structure, resulting in uniform pressure and velocity distributions within the inter-electrode gap. Furthermore, LPBF provides excellent material density and mechanical integrity, ensuring long-term durability in the electrolysis environment. Similarly, BJ is also a cost-effective method with high resolution, especially for large-scale production, making it an alternative candidate for fabricating the proposed electrode design. Among any other AM techniques, the required resolution cannot be obtained by electron beam melting (EBM) or directed energy deposition (DED). While nanoprinting technologies exist, their cost-effectiveness for large-scale applications remains doubtful. Given that each electrolysis full stack requires hundreds of these electrodes, a high production rate is essential to satisfy the growing demand for green hydrogen. Therefore, LPBF and BJ are the only viable options for scalable and precise manufacturing.

After printing, post-processing of the electrodes is essential to ensure optimal performance since the presence of surface irregularities significantly affect the flow performance. The printed parts often exhibit surface roughness and irregularities that disrupt the smooth flow of water and bubbles, leading to inefficient bubble extraction and potential gas crossover. Therefore, surface finishing processes, such as

electropolishing and chemical polishing are necessary to achieve the required surface roughness, enhancing flow performance and overall efficiency.

Once produced, each pair of electrodes, or an assembly of multiple pairs, can be placed in housings that are tightly sealed to maintain a fixed distance between the facing electrodes (anodes and cathodes). These housings can be produced by conventional manufacturing techniques, e.g. a combination of machining and injection molding, or with cost-efficient polymeric printing methods such as multijet fusion. An example of such an assembly is shown in Figure 6, illustrating a stack of electrolysis modules. In this diagram, each module, presented in green and blue, houses the cathode and the anode, respectively. As depicted, each module can accommodate multiple cathodes (or anodes), allowing for a high production rate and simplifying the assembly process. Such an assembly minimizes the need for piping, further reducing the costs.

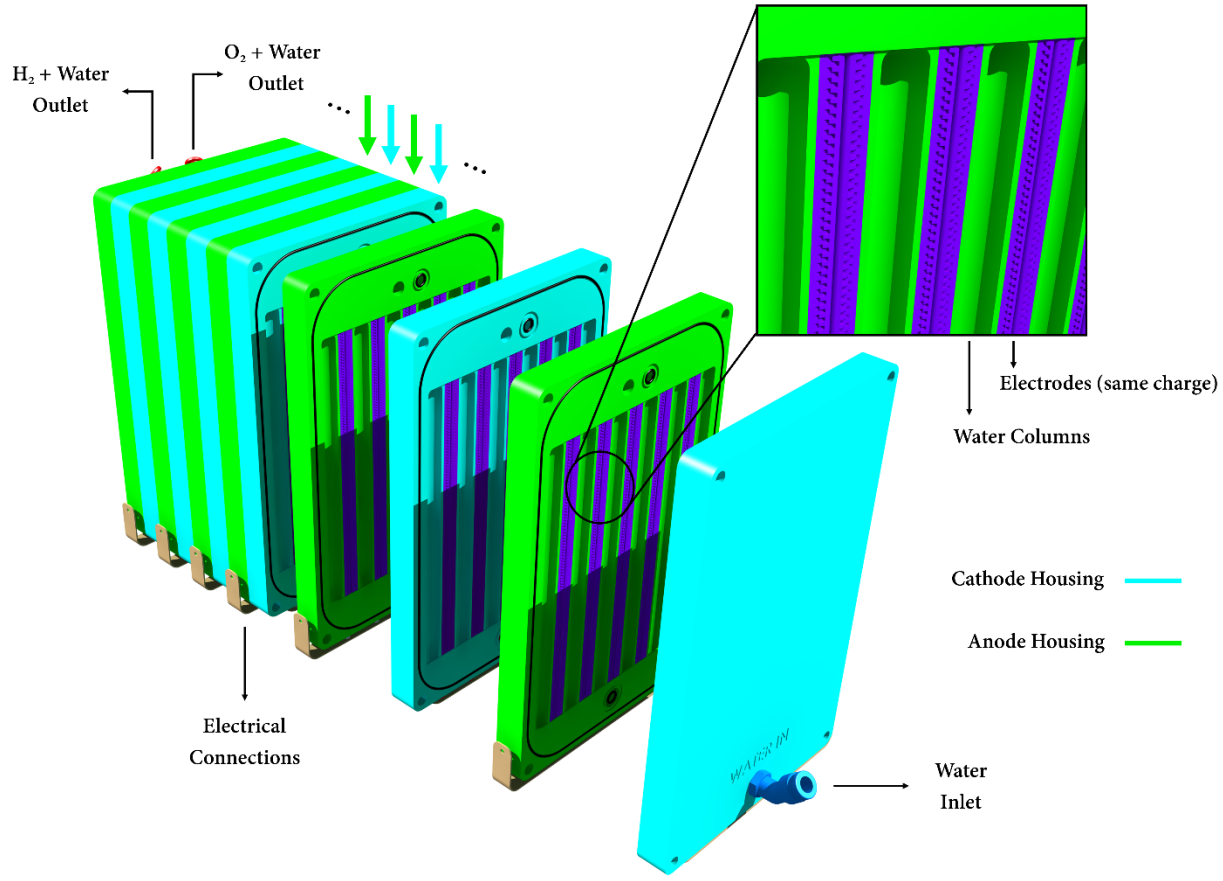

Figure 6: A proposed modular assembly for electrodes and a suitable housing design, consisting of a stack of modules, each incorporating several of same-charge electrodes, allowing water passage and product collection.

Part 5
Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean and continuous improvement

The proposed novel electrode design can be utilized by electrolyzer manufacturers of all sizes. With further optimization of key parameters, any electrolyzer manufacturer will be capable of manufacturing these electrodes and their associated housings, using a combination of additive manufacturing and conventional manufacturing. This design has the potential to reduce both the capital and operational costs of electrolyzers, which, in turn, could help drive increased demand for green hydrogen.

Therefore, the dissemination of the novel electrode design is critical to its widespread adoption and commercialization. The manufacturing coordination will likely involve a combination of electrolyzer manufacturers and research institutes. Electrolyzer manufacturers will potentially play a significant role in producing these electrodes. Meanwhile, research institutes, specializing in AM, will be responsible for facilitating smaller-scale production and initial testing, enabling iterative improvements and customization. This approach ensures flexibility in production and facilitates rapid innovation, especially in the early stages.

The novel electrode design will leverage existing digital and physical infrastructure, with a focus on the advanced capabilities of additive manufacturing, particularly LPBF and BJ. Digital tools such as CAD software and simulation platforms will be used to model and optimize the electrode geometry before printing, ensuring the most efficient design is selected, resulting in a lower production cost. The development of simulation modules or tools specially designed for electrochemical systems allows for more straightforward simulations on electrode performance. The use of LPBF and BJ in fabricating novel electrode designs will benefit from the growing amount of AM infrastructures that need customers and parts to generate revenue from their capital investments. Meanwhile, the quality of the printed electrodes heavily depends on the printing resolution. Therefore, the future improvement in AM technologies, e.g. cost reduction for high-resolution printers, as well as powder removal techniques could greatly enhance the effectiveness of the novel electrode design, while enabling the production of more complicated designs.

The serviceability of the electrode system will also be a key consideration. For reducing the operational cost, the electrodes must be easily maintained, replaced, or repaired when needed. The electrolysis stack is designed to allow for modularity, so that electrodes can be replaced without disassembling the entire system. Furthermore, sensors can be integrated to the electrolysis stack to track electrode performance and degradation over time, further improving serviceability.

Part 6
Cost Benefit/Value Analysis

A combination of additive manufacturing and stainless steel 316 has been reported to significantly reduce the green hydrogen cost. If widely used, 3D-printed stainless steel 316 electrodes can replace the existing expensive electrodes made of Pt, which is a rare element, further improving the sustainability of the industry. It has been suggested by Raza et al. that replacement of Pt@C electrodes with additively manufactured 316L electrodes can reduce price per kg H_2 from 5.5 USD down to 0.79 USD [16].

Table 1 shows the breakdown of production cost for electrodes manufactured via laser powder bed fusion. There are many other parameters that can be considered for part production costs [17], but a rough estimate of the total cost (C_{total}) for manufacturing single electrode can be estimated with the following equation:

$$C_{total} = C_{powder}M_{powder} + \frac{C_{machine}t_{machine} + C_{post}t_{post}}{n_{Build}}$$

By which, considering the parameters provided in the table, gives an estimated cost of $30 per electrode with a length of 100 mm.

Table 1. Estimation cost for electrode fabrication via laser powder bed fusion (per 33 mm electrode)

Term	Description	Value	Unit
C_{powder}	Powder cost	80	$/kg
M_{powder}	Powder mass used for building the part	0.0044	kg
$C_{machine}$	Operational cost of the machine	40	$/hr
$t_{machine}$	Building time	10	hr
n_{build}	Number of electrodes in one build	50	-
C_{post}	Post-processing cost	30	$/hr
t_{post}	Post-processing time	2	hr

Although the manufacturing of membrane-less electrolyzers containing novel electrode designs might be more costly compared with conventional flow-by and flow-through systems due to the geometry complexity and the application of additive manufacturing, the novel system offers high efficiency and high production rate while maintaining excellent gas purity. In comparison to AWE, PEM and AEM electrolyzers, even though the utilization of additive manufacturing might result in a higher manufacturing cost, the difference can be compensated by the elimination of membranes and the substitution of precious metals with cost-effective alloys in novel electrode designs.

Conventional AWE, PEM, and AEM electrolyzers have high operational costs due to their high maintenance needs, especially with membrane degradation and catalyst wear. On the other hand, membrane-less electrolyzers offer lower operational costs, primarily because they do not require membrane replacements and generally have lower maintenance requirements. In comparison to conventional membrane-less electrolyzers, the operational cost for the proposed novel system further decreases by optimizing bubble extraction efficiency and reducing energy consumption through improved flow.

The proposed innovative membrane-less system offers a more affordable alternative to conventional electrolyzers, especially when cost and scalability are major concerns. By enhancing efficiency, lowering operational costs, and reducing maintenance requirements, the novel design could significantly impact the economics of hydrogen production. Meanwhile, the use of additive manufacturing for electrode design also allows for scalable and customized production, which could further reduce costs over time.

Part 7
Conclusions

In this project, an innovative bio-inspired solution to address the trade-off between productivity, efficiency, and product purity of membrane-less electrolyzers for green hydrogen production is proposed and analytically evaluated. The design has the potential to reduce the cost of green hydrogen production, making it more affordable for industries such as agriculture and transportation, while also serving as a viable alternative to fossil fuels.

The novel electrode design combines the advantages of both flow-by and flow-through systems, optimizing bubble extraction efficiency, while maintaining uniform water velocity and pressure distribution. AM, particularly LPBF and BJ, plays a critical role in precisely controlling the surface texture and internal channels of the electrode, which are difficult to achieve via conventional manufacturing methods. The use of stainless steel 316L ensures printability, electrochemical stability and cost-effectiveness, compared with commonly used electrode materials, such as platinum. The electrode design uses current digital and physical infrastructures, including high-resolution AM systems, and software for modeling and simulation, for design optimization and integration into electrolysis stacks.

What sets this design apart is its ability to integrate AM with novel electrode designs to create more efficient and cost-effective electrolyzers. By eliminating the need for membranes, and using affordable alloys instead of precious metals, this approach lowers both capital cost and operational cost, making green hydrogen production more accessible. The highly modular design of electrolyzer stack also simplifies the maintenance procedure, with fewer components requiring replacement. Overall, the innovation in both design and manufacturing process could lead to a significant reduction in the cost of electrolyzers and facilitate wider adoption of green hydrogen technologies, contributing to a more sustainable future.

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