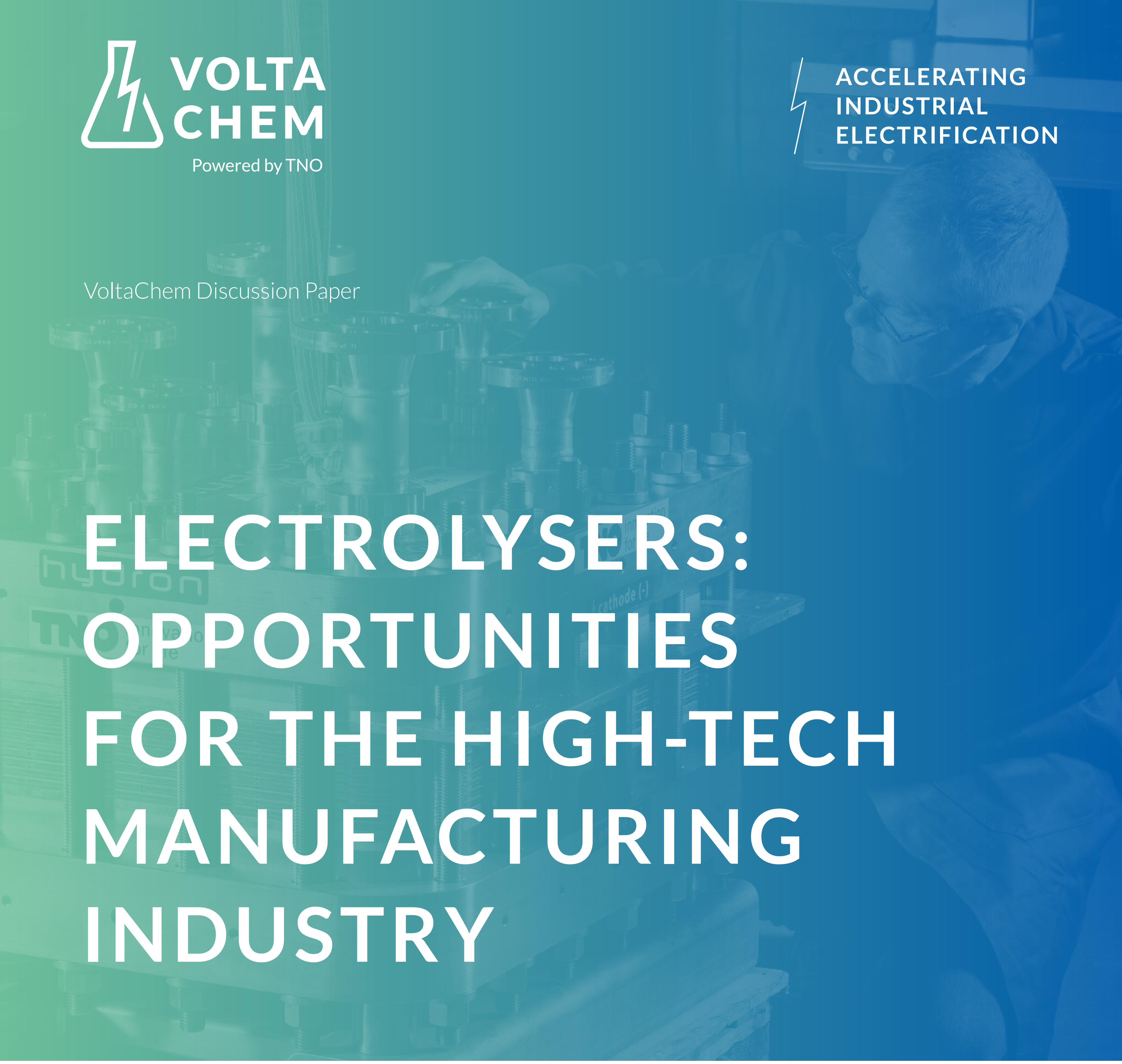

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VoltaChem Discussion Paper

ELECTROLYSERS: OPPORTUNITIES FOR THE HIGH-TECH MANUFACTURING INDUSTRY

The case of PEM

March 2023

TNO Authors

Roald A. A. Suurs
Rebecca Dowling
Oscar Diaz Morales
Emilio Manrique Ambriz
Lennart van der Burg
Matti M. van Schooneveld
Auke Jisk Kronemeijer
Arend de Groot

TNO Contributors

Alfredo Mameli
Anca Anastasopol
Mahmoud Ameen
Martijn de Graaff

Illustrative cases provided by industrial companies

Ahmad Harbiye	VECO Precision
Paul Poodt	SparkNano
Peter Visser	SALD
Niels Schouten	VSParticle
René Hauser	Delft IMP

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EXECUTIVE SUMMARY

The global challenge of the current climate crisis presses governments, businesses and knowledge organisations all over the world to mobilise behind energy saving, phasing out fossil energy and rapid deployment of renewable energy and green hydrogen. The latter is needed primarily to decarbonise the heavy industry, aviation and maritime sectors. Given the large volumes of green hydrogen required for the energy transition, there is a need to vastly ramp up the capacity for green hydrogen production through electrolysis in the coming decade.

Currently, available electrolysis technologies and electrolyser manufacturing capacity are not yet fit to match the expected demand.[1] To meet the energy transition challenge, manufacturing capacity of electrolysers has to scale up while simultaneously improving the design of the technology on a fundamental level, from its basic materials, to components, to entire system architecture.

This paper illustrates how the challenge of rapid upscaling and improving electrolysers can be addressed by using high-tech manufacturing technologies as currently applied for the production of thin-film electronics. Generally speaking, such technologies leverage the potential of massive economies of scale and at the same time open up novel possibilities for product design.

The scope here is limited to the case of so-called Proton Exchange Membrane (PEM) water electrolysers to allow for discussions on the component level. The PEM electrolyser cell comprises multiple components that are very thin layers for which the functionality highly depends on their interfaces. This architecture lends itself well to high-tech manufacturing solutions adapted to the production of thin-film large surface components with highly integrated functionality. However, many of the discussed principles are equally applicable to the alternative technologies, which are Solid Oxide Electrolysis (SOE), Anion Exchange Membrane (AEM) and Alkaline Water Electrolysis (AWE).

Important Technological Challenges of PEM Electrolysers

This paper identifies four crucial technological challenges for PEM electrolysers that could be overcome by the applications of high-tech manufacturing. Firstly, expensive and stable materials are required, due to the highly corrosive environment within the system. Secondly, there is a need to facilitate efficient contact between the different layers within the electrolyser cell, requiring delicate optimisation of the three-dimen-

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[1] IEA, „*Global Hydrogen Review* 2022," IEA, Paris , 2022.

sional structure within those layers. Thirdly, transport losses within the electrolyser must be reduced to increase the efficiency of the overall electrolysis process. Finally, the catalyst should have a much higher surface area than the geometrical area of the membrane. Addressing these four challenges is necessary to operate the electrolyser at a high current density to produce as much hydrogen as possible.

Opportunities for the High-Tech Manufacturing Industry

Solving the stated challenges involves trade-offs. A solution to one challenge may have negative effects on another. Typically, this means navigating between operating efficiency, durability and costs. High-tech production technologies may partially surpass these critical trade-offs. To understand the future technological development of PEM electrolysis and the associated opportunities for the high-tech manufacturing industry, it is helpful to distinguish between three generations of innovation as depicted in the figure below.

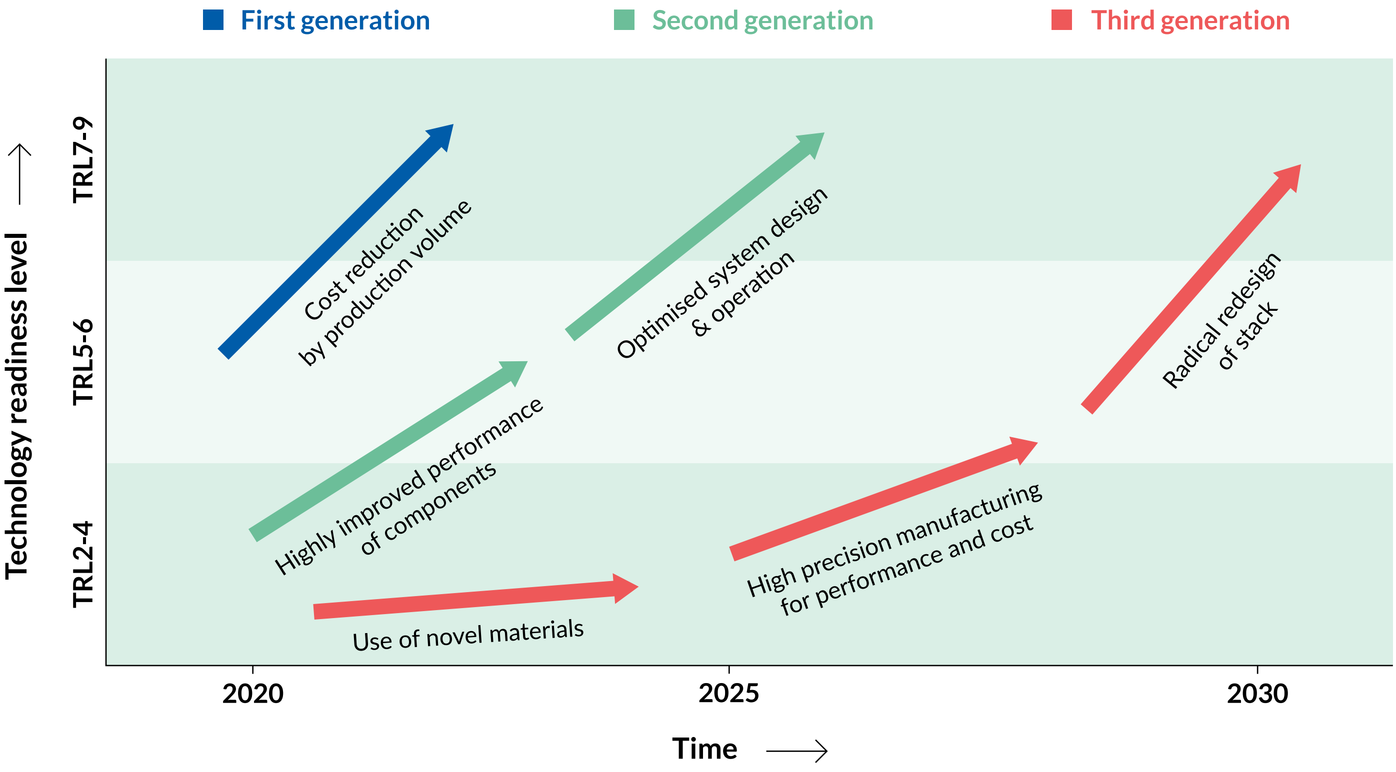

Figure 0. Three generations of PEM electrolysers are expected to mature in the next decades. Note that while presented here as three distinct forms of innovation, the lines between the generations are not clearly defined and intermediate steps exist. Note also that although we show an indicative timeline on our roadmap image, it doesn't necessarily mean that the second generation will develop faster than the third generation. This depends on strategy, the effort and focus put into research and development (Source: TNO).

The schematic roadmap shows how the three technology generations are characterised by solutions with varying technological maturity in time.

1. The **first generation** assumes cost reduction through increasing volumes and standardisation of currently available technology.

2. Innovation in the **second generation** of PEM electrolysers is focused on optimising the performance of separate components and the interfaces between different layers in the stack.

3. The **third generation** focuses on producing more efficient and flexible electrolyser systems, with a radically new (system) architecture.

To provide insight in the specifics of the opportunities involved, several innovative approaches, and the companies involved, are highlighted throughout the paper.

Recommendations

This paper projects a plausible future where the improvement and scale-up of electrolysis technology go hand in hand. This is the promise that the high-tech manufacturing sector brings. At the same time, the three different technology generations presented above are by no means a given. They represent opportunities that, in order to become manifest, need to be acted on. The following recommendations serve as main guidelines for concerted strategic action.

Policy and Market Constraints

Key Challenge: Given EU wide ambitions to ramp up electrolysis capacity, the full potential of the European technology ecosystem needs to be utilised for implementing first generation electrolysers while simultaneously accelerating the development and utilisation of the second- and third-generation electrolysers developed to be more efficient and to have an inherently circular design.

Actions: The EU and its member states should – in addition to current targets for green hydrogen production capacity – set progressive market targets to specifically stimulate development of second-generation and third-generation production capacity; for instance: 100MW in 2028 – 500MW in 2030 but this should be discussed. These targets should be backed up by policy incentives and embedded in a European technology leadership strategy. This is to avoid an early lock-in into first-generation electrolysis technologies and to improve chances to meet the required growth ambitions beyond 2030.

Supply Chain & Ecosystem

Key Challenge: Given the currently still limited and poorly articulated market demand, even with policy targets in place, the knowledge exchange, cooperation and integration of (potential) value chain partners from different sectors occurs only haphazardly. The risk is that this will hamper the timely development of advanced production technologies and hence negatively impact the speed and direction of the energy transition.

Actions: For the electrolyser manufacturing industry to gain momentum, it is critical to not merely act as suppliers to the first commercial projects, but to work together towards shared industry milestones. This can be accelerated by developing a EU wide next-generation electrolyser program that is dedicated to the accelerated development, implementation and scale up of second- and third-generation EU manufactured technologies. The program should provide a stimulus for actually working together of manufacturing partners. First on research and engineering, and then especially on implementation in close collaboration with OEMs and process industry. The program should facilitate an infrastructure for testing and validation on the level of 1-5 MW-systems.

Research & Innovation

Key Challenge: The EU and its member states are well positioned as a technology leader in the field of hydrogen and fuel cells technology. Still the field, with its expertise, facilities and networks is rather fragmented and unaligned. The risk is that insights and lessons learnt from innovation and experimentation within the context of specific projects or within certain member states does not add up and contribute to a common ambition. The challenge is to accelerate learning and innovation by better leveraging the knowledge position and technology infrastructure of the entire European research ecosystem. This could position the EU electrolyser manufacturing industry to be a global frontrunner.

Actions: It is critical to work towards a shared EU R&D infrastructure for testing and validation by aligning and connecting facilities. The benefit is that European industries gain access to a broad basis of support for testing, validation and benchmarking. Also, large investments in key demonstrator facilities, for higher TRL, become more viable. For all upcoming publicly funded pilots and demonstration projects, data sharing and monitoring of system performance should be a prerequisite to accelerate learning.

1. INTRODUCTION

The unprecedented challenge of improving and upscaling electrolysis technology

The global challenge of the current climate crisis presses governments, businesses and knowledge organisations all over the world to mobilise behind carbon-reducing innovations, such as large-scale renewable energy solutions. The capacity to economically produce, store, transport and use carbon-neutral hydrogen as part of a system centred on renewable energy is widely considered an enabler, if not a requirement, for such developments. Given the enormous quantities of green hydrogen required for the energy transition, there is an urgent need to ramp up electrolysis capacity, in the coming decade.[2] To put this in numbers; the International Energy Agency projects a production capacity of 17 GW by 2026 from less than a GW installed today. For Europe, the magnitude of this challenge is reflected in the European Green Deal and the European Hydrogen Strategy which sets a target for 6 GW of installed electrolyser capacity by 2024, and 2x40 GW by 2030[3]. Billions of euros will be allocated as a public stimulus for innovation and upscaling. As shown in Figure 1, this implies a growth curve, and related market development, for the coming decade that is hard to imagine.

Ambitious policy targets and funding plans create business opportunities, but also put pressure on the industry as the currently available electrolysers on the market are not yet optimised to meet the energy transition's demands. To meet the energy transition challenge, mass manufacturing of electrolysers has to start now while simultaneously improving their design on a fundamental level, from its basic materials, to components, to entire system architecture. The technology has to be improved to handle more power (higher current density while keeping overpotentials low), improve (conversion) efficiency and enable larger sizes without using too much (costly and scarce) materials, all while guaranteeing the integrity of the system over a sufficiently long lifetime.

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[2] Besides electrolysis, low carbon hydrogen can be generated from biomass or natural gas in combination with Carbon Capture and Storage (CCS), so multiple alternatives exist. Still, when it comes to accommodating the influx of huge quantities of renewable electricity in the grid, electrolysis in combination with a hydrogen storage and transport infrastructure, is deemed critical.

[3] Several hydrogen strategies from European member states also have quantified targets for electrolysers according to their National Hydrogen Strategies looking at 2030 horizon, e.g. 6.5 GW in France, 5 GW in Germany, 3-4 GW in the Netherlands 1 GW in Portugal and 4 GW in Spain.

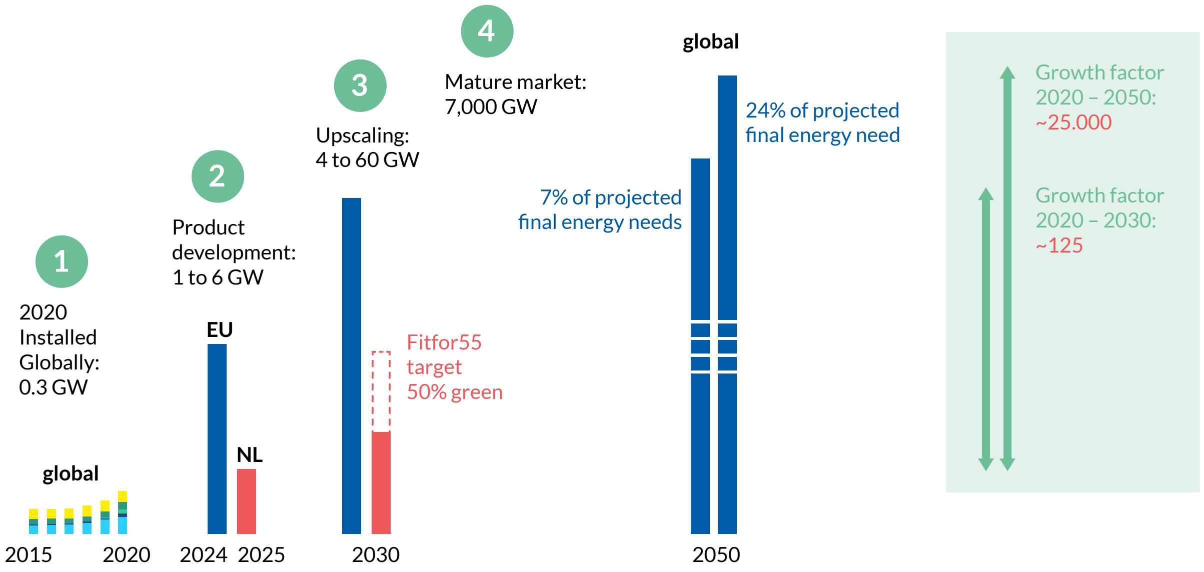

Figure 1. Projected market development for electrolysis capacity. Source: IEA (2021), Global installed electrolysis capacity by region , 2015-2020 (link), Bloomberg, Hydrogen Economy Outlook – Key messages, March 2020 (link), adapted by TNO.

Opportunities for the high-tech manufacturing industry

This paper illustrates how the challenge of rapid upscaling and improving electrolysers can be met by using high-tech manufacturing technologies as currently applied for the production of thin-film electronics. As an example, imagine a technology that enables the deposition of layers of atomic thickness, radically improving material efficiency while simultaneously enabling automated production according to the highest standards of quality control at high throughput. This spatial Atomic Layer Deposition is a proven technology for the production of electronics and is currently being adopted to apply catalysts for electrolyser components. Note that this involves much more than mere automation.

Generally speaking, such technologies leverage the potential of massive economies of scale and at the same time open up novel possibilities for product design.[4] To illustrate the specifics of this broad argument, the scope of this paper is limited to the case of so-called Proton Exchange Membrane (PEM) water electrolysers. However, many of the discussed principles are equally applicable to the alternative technologies (see Section 2 for a description).

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[4] The high-tech manufacturing sector is historically well known for the production of electronic chips, flat panel displays (thin film) photovoltaics and batteries etc.

Box 1: The PEM water electrolyser value chains

The value chain for PEM electrolysers consists of three segments as depicted in Figure 2.

1. The green hydrogen value chain consisting of hydrogen users, distributors and producers on the one end, and electricity providers and grid operators on the other end. Within this value chain, hydrogen producers can be seen as the customers for electrolyser technologies. Market demand for the companies involved is expected to grow drastically, due to governmental regulations and green hydrogen mandates on the one end and growth of renewable and nuclear energy on the other end.

2. The providers of the electrolysers, consisting of EPC contractors, system integrators / OEM's and component providers. The companies involved currently attract a lot of investments, because of high expectations of green hydrogen worldwide. These companies are expected to deliver high quality equipment in multiple generations over the next decades.

3. The providers of High-Tech equipment and materials will deliver the key components and unique technologies for next-generation high-efficient and durable electrolysers. These are, for a large part, players that are currently active in other areas like semiconductor, automotive and gas treatment industries.

INDUSTRIAL VALUE CHAINS OF (GREEN) HYDROGEN

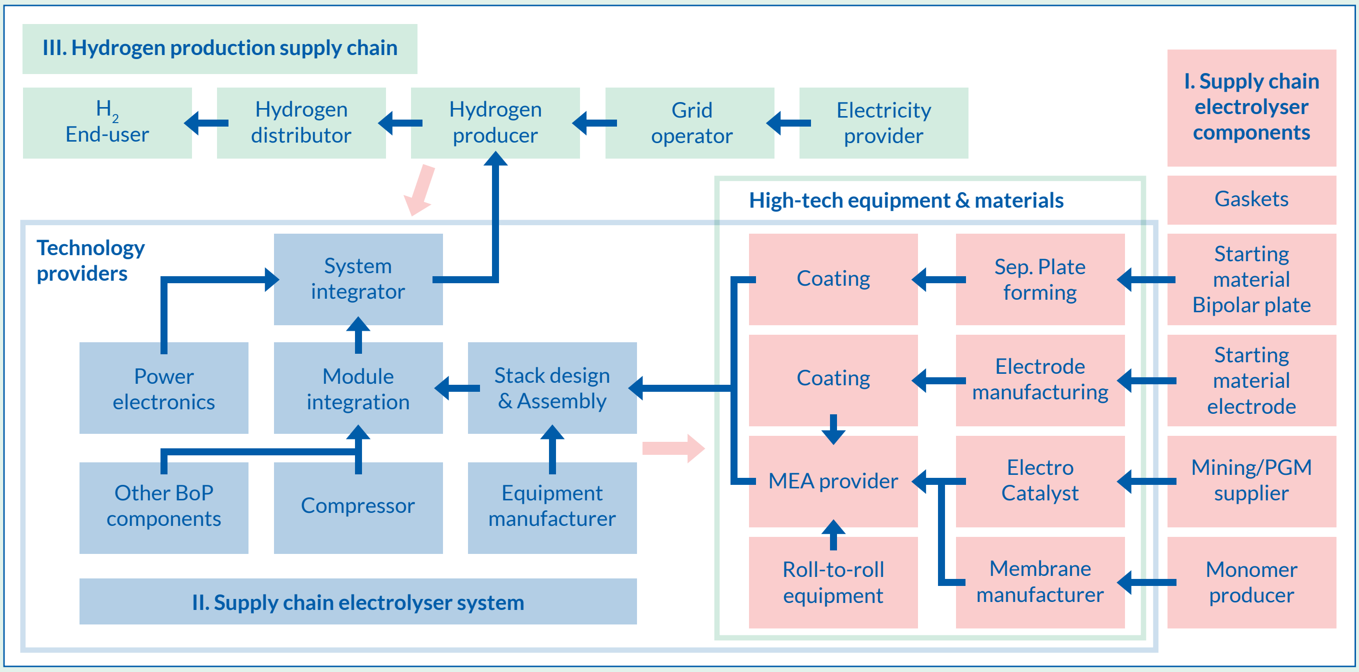

Figure 2. Value chain for PEM water electrolysers. Source: TNO.

To provide insight in the specifics of the opportunities involved, several innovative approaches, and the companies involved, are highlighted throughout the paper. Moreover, the technologies are projected on a time horizon by connecting them to the three technology generations.

A schematic overview of the businesses involved in PEM electrolyser manufacturing is provided in "Box 1" on page 11. Note that High-Tech manufacturing companies are currently positioned as technology suppliers that currently only have a small stake in the production of electrolyser systems. This poses a challenge as radical innovation requires close integration of manufacturing expertise, technological knowledge and market intelligence.

All things considered, further development and upscaling of High-Tech solutions require an intimate bridging of the world of (industrial) electrochemistry with the world of high-tech manufacturing and thin film electronics. Moreover, given the nature of the current value chain, where equipment suppliers are typically dependent on a small number of OEMs, a concerted efforted is needed to push for radical innovations.

This discussion paper is meant as a starting point for dialogue across disciplines. At TNO, as well as within the VoltaChem and TNO at Holst Centre shared innovation programs, we believe that it is this alignment of disciplines and expertise areas that will provide opportunities for timely development of advanced electrolysis technology.

Reading guide

In the following sections the electrolysis technology will be introduced in some more detail, so as to provide a basic reference for the materials and components involved, as well as critical challenges to be addressed (Section 2). Next, the opportunities of the high-tech manufacturing industry will be identified and placed on a time horizon by relating them to three subsequent technology generations (Section 3). Several examples will be highlighted, addressing, some frontrunning companies involved, as well as some focal points of our collaborative research and innovation agendas. Finally, a set of recommendations will be formulated that enable high-tech's full potential to improve electrolyser manufacturing (Section 4).

2. ELECTROLYSERS AND HOW THEY ARE MADE

On electrolysers

Before delving deeper into the opportunities that come with high-tech manufacturing, it is relevant to introduce the basics of electrolysis technology and point out the main challenges and trade-offs that currently exist. Water electrolysis is the process of splitting water into hydrogen (H_2) and oxygen (O_2) gases with the use of electricity. The water-splitting process takes place in a device: the electrolyser. An electrolyser has two electrically conductive components where water splitting happens (electrodes), separated by a liquid, polymeric or solid layer that conducts ions (electrolyte). Electrolysers operate with one negatively-charged electrode (cathode) and one positively-charged electrode (anode). Inside the electrolyser cell, water is split into hydrogen gas at the cathode and oxygen gas at the anode.

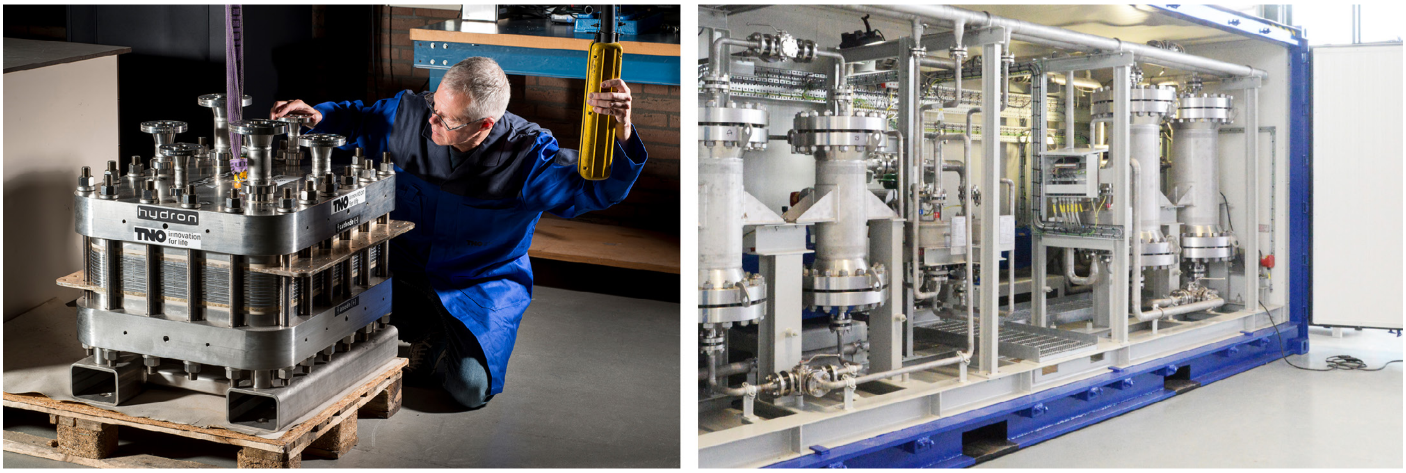

Figure 3. TNO electrolyser R&D stack (left) and balance of plant (right) placed at TNO research Faraday lab in Petten and in the MW-test centre Groningen (the Netherlands).

A variety of electrolysis technologies are expected to play a role in our future energy system and are considered relevant candidates for applications of high-tech manufacturing. Currently, the two dominant technologies on the market are Proton Exchange Membrane Water Electrolysis (PEMWE) and Alkaline Water Electrolysis (AWE). Other promising technologies are Anion Exchange Membrane (AEM) and Solid Oxide Electrolysis (SOE). For this paper the focus lies on discussing such options for PEM electrolysers, as high-tech manufacturing technologies are expected to play an important role in scaling up this technology to gigawatt scale in the coming decades. Many of the discussed opportunities for the high-tech sector are expected to be applicable to the alternative water electrolysis technologies as well.

PEM electrolysis technology is suitable to generate green hydrogen at a large scale because it has high hydrogen production rates and is considered to operate relatively well with intermittent renewable electricity sources. The PEM electrolyser system consists of a so-called balance of plant, including compressor, power electronics, water treatment etc., and the electrolyser stack. This stack, which can be regarded as the heart of the electrolyser, is made up of cells, each of which performs the primary electrolysis reaction: water splitting. As multiple of such cells are combined the capacity to use electricity and produce hydrogen increases.

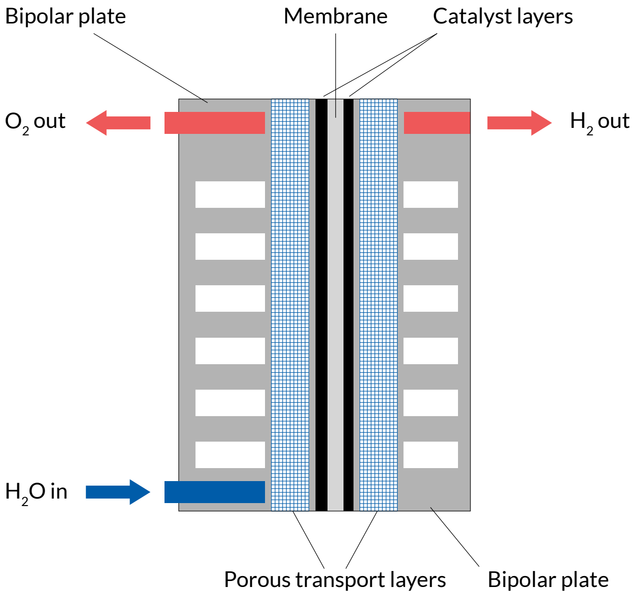

Figure 4. Schematic representation of a PEM electrolyser cell. Source: A. Mayyas, M. Ruth, B. Pivovar, G. Bender en K. Wipke, „Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers," National Renewable Energy Laboratory, Golden, CO., 2019.

The PEM electrolyser cell is made up of multiple thin layers for which their functionality highly depends on their interfaces. This architecture lends itself very well for high-tech manufacturing solutions, which are able to produce large surface thin films with highly integrated functionality. With respect to the electrolyser cell, the following functions can be distinguished:

- **The bipolar plates** (BPP) separate the cells within a stack and conduct electricity between the cells. They also provide mechanical support, distribute water inside the cell and carry generated gases to the outlet, through channels that facilitate the transport of water, hydrogen and oxygen inside of the stack.

- The **porous transport layer** (PTL) is an electron conducting porous medium that enhances water, gas and heat transport between the BPP and the heart of the electrolyser: the membrane electrode assembly (see below).

- The **catalysts** layers (made of platinum group metals) accelerate the reaction of water into oxygen and protons at the anode side, and the conversion of protons to hydrogen at the cathode side.

- In the middle of the cell a proton exchange **membrane** is placed, that enables passage of protons and prevents crossover of gaseous products.

- The combination of membrane and catalyst layers is also called a **membrane electrode assembly** (MEA). This electrolyser component can be manufactured in several configurations. For example, catalyst layers can be directly deposited onto the proton exchange membrane resulting in a so-called Catalyst Coated Membrane (CCM). Another approach is to deposit the catalysts layers onto the PTL, resulting in a Catalyst Coated Substrate (CCS). The proton exchange membrane is then sandwiched between two catalyst-coated PTLs.

Technological challenges and high-tech solutions

Four important technological challenges are identified for PEM electrolysers which could be overcome by application of high-tech manufacturing technologies. Firstly, **expensive and stable materials** are required due to the highly corrosive environment within the PEM cell. To efficiently drive the water splitting process with electricity, a high concentration of ions (for example H^+ or OH^-) is needed. This requirement, together with a high concentration of oxygen and hydrogen gases and high current densities, favours the conditions for corrosion, which lead to performance and mechanical degradation of electrolysers. Furthermore, because the water-splitting process is slow, catalysts are needed to accelerate the process to an acceptable rate for the commercial production of green hydrogen. Combined with the already limited choices of catalysts materials, the resulting need for critical raw materials, such as iridium, pose an important bottleneck to the scale up of PEM electrolyser manufacturing. Here high-tech manufacturing techniques could help producing stable and uniform catalyst layers with limited material usage while simultaneously optimising stability of such a layer under operation.[5]

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[5] Techniques such as ultrasonic spray coating or spatial atomic layer deposition (sALD) or a dry nanoparticle synthesis and deposition process based on spark ablation. Source: D. Kulkarni, A. Huynh, P. Satjaritanun, M. O'Brien, S. Shimpalee en D. Parkinson, „Elucidating effects of catalyst loadings and porous transport layer morphologies on operation of proton exchange membrane water electrolyzers," Applied Catalysis B: Environmental, vol. 308, 2022.

Secondly, there is a **need for an optimised three dimensional structure** to facilitate efficient contact between the different layers within the electrolyser cell. Water splitting is an electrochemical process, which requires a three-phase boundary (TPB): a phase transporting ions (electrolyte), a phase conducting electrons (electrodes) and a phase transporting reactants and products (porous transport layers). In the case of a PEM electrolyser, the TPB consists of a membrane conducting ions and a porous electronic conductive material acting both as electrode and carrier of water and product gases. High-tech manufacturing has great potential to tune the boundaries in this triple interface to minimize the use of critical raw materials as catalyst loading and maximise the utilisation, enhance mass transport of reactants into the active interface and reduce ohmic loses due to poor electrical contact or gas bubbles formation.

Thirdly, **transport losses within the cell must be reduced** to increase the efficiency of the overall electrolysis process. An important cause of these losses is the transport of ions. In the PEM electrolyser the ion transport takes place in the catalyst layer and in the membrane separating both catalyst layers. The challenge is therefore to make these layers as thin as possible. However, reducing the membrane thickness causes an important trade-off, because a thinner membrane is less mechanically strong and less resistant to the crossover of gases. Hydrogen crossover reduces performance and poses a major safety issue, as the combination of hydrogen and oxygen in presence of a metal catalyst like Pt could lead to explosions. An important high-tech solution is the optimisation of the reinforcement structure of the membrane to improve through-plane conductivity while maintaining cross-plane strength. Furthermore, multilayer membrane or hybrid concepts could overcome material property issues by making smart combinations of multiple materials.

Fourthly, the **catalyst should have a much higher surface area** than the geometrical area of the membrane. Since the materials used in electrolysis cells are expensive and scarce, it is necessary to operate the electrolyser at a high current density (A/cm^2) to produce as much hydrogen as possible. In the PEM electrolyser, this optimum current density (a compromise between efficiency and hydrogen production per surface area) is dictated by the losses in the membrane. However, to “keep up” with the membrane, a high electrochemically active catalyst area is needed, which must be larger than the geometrical area. High-tech manufacturing technologies like 3D printing and micro or nano-lithography can be used to produce PTLs with tuned micro- and meso-structures with large surface areas, while advanced deposition techniques such as sALD can deposit the catalyst layer to maximise the electrochemically active catalyst area.

See Appendix 1 for a full overview of components, their functionality, critical design trade-offs and potential high-tech solutions.

Box 2: A word on economies of scale

A key driver in scaling up and commercialising electrolysis capacity is the costs. There are three main cost contributors: the electricity price, the capital expenditure of the electrolyser and the amount of operational full load hours.

To reduce the impact of capital costs, scale-up is in itself an opportunity for cost reduction. After all, large series production of systems, and high-volume manufacturing of components, will reduce the marginal costs of production. This argument is often used by advocates of solutions from the high-tech manufacturing sector.

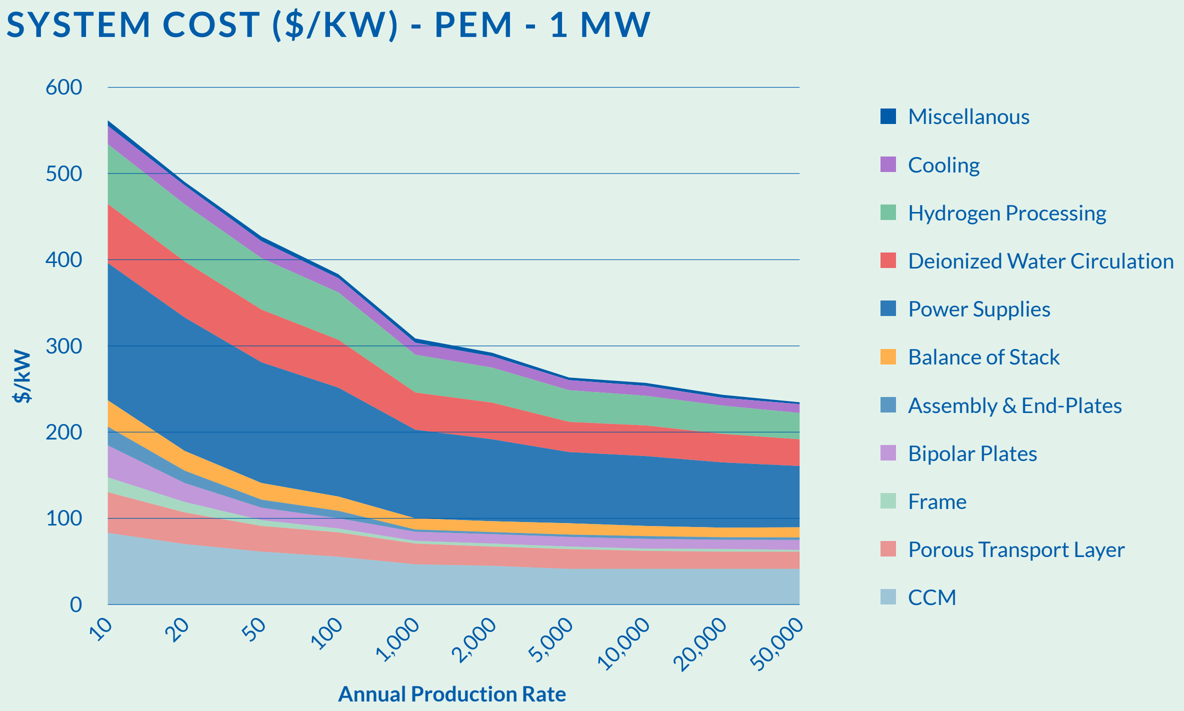

Figure 5. 1 MW PEM electrolyser system cost at different annual production rates. Source: A. Mayyas, M. Ruth, B. Pivovar, G. Bender en K. Wipke, „Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers," National Renewable Energy Laboratory, Golden, CO., 2019.

Various studies provide projections of cost reduction as a function of cumulative installed capacity or manufacturing scale.[6] TNO, withing the framework of the VoltaChem program, has developed a meta-analysis of such projections.[7] Some important observations are:

- To reach a cumulative installed capacity of 100 GW in 2030, annual installation

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[6] IRENA, „*Green Hydrogen Cost Reduction: Scaling up electrolysers to meet the 1.5 C climate goal.*," International Renewable Energy Agency, Abu Dhabi, 2020.

[7] TNO, „*Projections of electrolyzer investment cost reduction through learning curve analysis.*," 2022.

needs to **double each year** until 2030. The **learning rate – or costs reduction as a function of cumulative installed capacity** – of electrolyser technologies varies between 12-20%.

- However the learning rate will differ between PEM, Alkaline, SOE. (i.e. LR for portable lithium Ion batteries is 30%; lead batteries only 4%).
- In terms of learning rates, the manufacturing, assembling and BoP technology for Alkaline and PEM is **fairly comparable**. However PEM and SOE can **benefit from fuel cell developments**. This effect is generally not included in projections, yet may benefit cost reductions.

All in all, high-tech manufacturing solutions can substantially contribute to ‘going down’ the learning curve. But at the same time, in order to become feasible, require a certain minimum market volume and level of standardization. This calls for an approach where production and market activation are simultaneously targeted by strategic players and governments alike.

3. TECHNICAL OPPORTUNITIES FOR HIGH-TECH MANUFACTURING

High-tech production technologies offer a vast opportunity to solve trade-offs in performance while reducing electrolyser costs. To understand the future technological development of PEM electrolysis and the associated opportunities for the high-tech manufacturing industry, it is useful to distinguish three generations of innovation:

The first generation assumes cost reduction through increasing volumes and standardisation of currently available technology. The first-generation PEM technology is currently at a technology readiness level (TRL) of 9 and provides the shortest route to market scale-up compared to the other two generations.

The second generation revolves around improving performance at the level of materials and separate components. Within this generation, there is a focus on extremely thin layers to reduce the use of critical materials, such as platinum, gold and iridium, or to replace problematic materials with alternatives.

The third generation focuses on producing more efficient and flexible electrolyser systems, with a radically new (system) architecture. For example, instead of putting the catalyst on the membrane, it could be deposited on a dedicated PTL structure. The deposition process can be tuned to maximise the amount of active catalyst.

A visual overview is presented in Figure 6. The schematic roadmap shows how the three technology generations are characterised by solutions with varying technological maturity in time. It should be stressed that besides solving technological issues, hence increasing TRL, the actual investments in the manufacturing supply chain will depend for a large part on market demand. See “Box 2” on page 17 for a related argument on economies of scale.

In the following sections, each of the technology generations will be explored further.

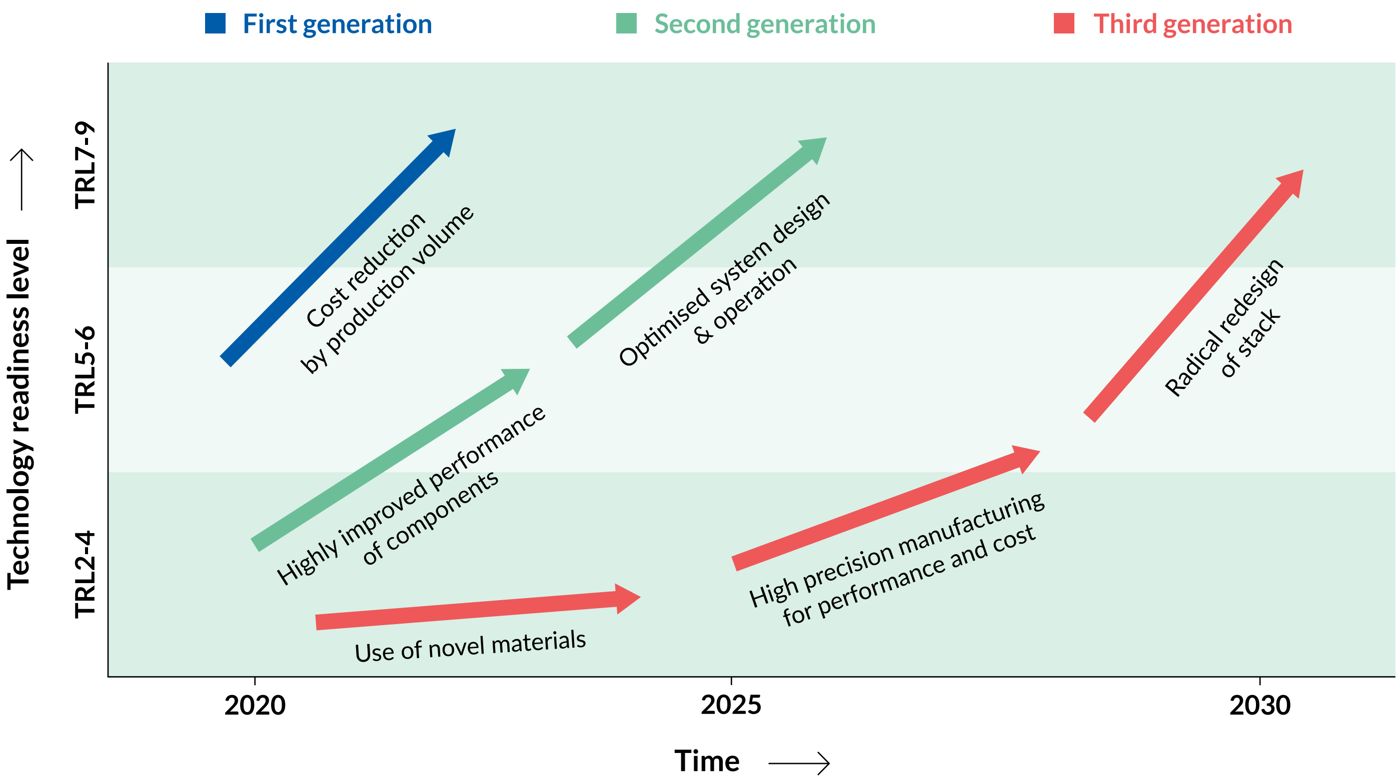

Figure 6. Three generations of PEM electrolysers are expected to mature in the next decades. Note that while presented here as three distinct forms of innovation, the lines between the generations are not clearly defined and intermediate steps exist. Note also that although we show an indicative timeline on our roadmap image, it doesn't necessarily mean that the second generation will develop faster than the third generation. This depends on strategy, the effort and focus put into research and development (Source: TNO).

First Generation: High(er) Volume Manufacturing

Currently, most electrolyser components are produced in small volumes, through batch processes, and individual stacks are assembled manually. The goal is to move towards high throughput, continuous, (semi-)automated manufacturing lines, to reduce the cost of electrolyser components. Within the first generation, the challenge is therefore to accelerate the scale-up of electrolyser production, using the currently dominant design of PEM electrolysers (based on catalyst coated membranes, CCM).

The appropriate choice of manufacturing technology follows from the product design, the required production volumes and the costs of the technology. Multiple opportunities exist here. For example, there is a need to scale-up and improve the continuity of the production of perfluorosulfonic acid (PFSA) membranes, such as Nafion™, Fumapem™

or Flemion™[8], since the PFSA membrane is an important contributor to total stack cost.[9] Another example is the production of CCM, where the dominant deposition methods are spray coating and screen printing. Technologies such as slot-die and doctor blade coating represent alternatives, which could improve both the speed of the CCM manufacturing process and the quality of the coatings.[10]

The first-generation PEM technology is currently at a technology readiness level (TRL) of 9 and provides the shortest route to market scale-up, compared to the other two generations. Based on the comparatively high TRL, it is likely that the first few GWs of electrolyser capacity up to 2027 will be produced by scaling up of current technology using existing materials and components. For a large part this is already happening and high-tech solutions will have a fairly limited impact on these developments. Yet, there are opportunities for companies that can already provide 'drop-in' solutions in the coming years. (See "Box 3" on page 22 and "Box 4" on page 23). Note that both showcases involve solutions for improving current production processes while still promising to qualitatively improve electrolyser components. This positions them 'halfway' into the second-generation technologies.

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[8] S. Shiva Kumar en V. Himabindu, „*Hydrogen production by PEM water electrolysis – A review*," Materials Science for Energy Technologies, vol. 2, nr. 3, pp. 442-454, 2019.

[9] A. Mayyas, M. Ruth, B. Pivovar, G. Bender en K. Wipke, „*Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers*," National Renewable Energy Laboratory, Golden, CO., 2019.

[10] Idem.

Box 3: Electroforming technology to allow high volume production of optimised electrodes

Electroforming is an additive manufacturing process that gives great freedom of design. Nearly any surface texture can be made to achieve large surface areas and high open area. To enhance surface properties various coating processes are available.

VECO already produces optimised Nickel electrodes for Alkaline electrolysers. These can be produced with a wide variety of hole-size and shapes as well as 3-D structures (pillars). This involves a mature and high-volume production process (TRL 9) ready to supply electrodes up to 1.4x1.4m2 with a capacity of >1000m2/y. VECO will continue to engage its materials and process expertise to optimise the electrode performance by co-design and co-development with partners, as to improve their electrode efficiency.

Although currently focused on components for alkaline electrolysis, specific developments could be undertaken, building on this manufacturing technology, for AEM, SOE or PEM electrolyser components.

Source: Ahmad Harbiye - Veco BV.

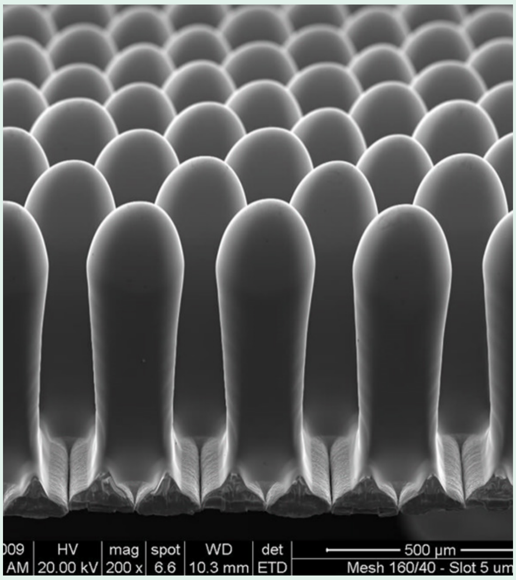

Figure 7. 3D structure of Nickel electrode produced through electroforming.

Box 4: Spark ablation enabling mass production of CCMs

Spark ablation converts bulk materials (metals or semiconductors) into nanoparticles suspended in a gas stream, which directly deposits the nanoparticles on the desired substrate (e.g. electrolyser membranes or PTLs).

Because this process doesn't require any liquids, it enables the manufacturing of catalyst layers with very large active area (small and very pure nanoparticles arranged as a porous thin film). This enables catalyst layers with high performance and very low precious metal content. This process also significantly lowers the production costs of catalyst layers, as it converts bulk materials (e.g. iridium and platinum) into a deposited catalyst layer in a single step, without requiring any chemicals or evaporation steps. Besides developing mass production equipment, VSPARTICLE also provides equipment for rapid development of new catalysts, by enabling rapid synthesis and screening of new catalyst materials.

VSPARTICLE's R&D tools are currently on the market, with a process development tool (also suitable for small series production) following soon, and a mass production tool currently under development. VSPARTICLE is actively collaborating with manufacturers of catalyst-coated membranes and electrolysers to optimize the catalyst coatings in their products. *Source: Niels Schouten - VSPARTICLE*

Figure 8. VSPARTICLE's R&D, process development and mass production tools (from left to right).

Second Generation: Components and materials

Innovation in the second-generation PEM electrolysers is focused on optimising the performance of separate components and the interfaces between different layers in the stack. The general system architecture remains the same as the currently dominant technology, but modifications to the different components improve the overall performance of the electrolyser.

Within this generation, there is a focus on handling of extremely thin layers to reduce the use of critical materials, such as platinum, gold and iridium or to replace them with alternatives. For example, it is possible to optimise the performance of the PTL by applying dedicated (3D) microstructures using lithographic and additive printing approaches. Also, the composition of catalyst coatings can be changed to improve adhesion to the membrane, minimise PTL corrosion or reduce iridium loadings. For BPP's it is possible to replace solid titanium components with steel components coated with micron layers of titanium, thereby reducing costs. See Boxes 5-7 for examples of solutions that are currently being developed on the component level.

A generally promising manufacturing technology for second-generation PEM technology is atomic layer deposition (ALD), a thin-film deposition technique which results in highly uniform layers, even on 3D structures, with minimal material wastage. For instance, thin layers of PGM can be deposited on particles to create a core shell catalyst particle that only uses limited amounts of metal to arrive at the same catalytic effect in the production of the catalyst coated membrane. Spatial ALD (sALD) is a variant of ALD that applies atmospheric pressure instead of vacuum operation, enabling higher throughput over larger surface areas. Spatial ALD is a very well-scalable technology that is already available for more mature PV, battery and fuel cell manufacturing applications.

On average, the innovations associated with the second-generation technologies are at a lower TRL of approximately 5 to 6, compared to the first generation. Also, most of the technologies involved presume an established market for (standardised) high quality PEM components. (See Box 2 for a full argumentation.)

Box 5: Spatial-ALD of low-loading catalyst layers and anti-corrosion/protective layers

Using S-ALD, highly conformal and low-loading-catalyst films can be applied on state-of-the art PEM stack components, such as the PTL, the Decal stack or the membrane, using well-known low-cost catalyst support materials (e.g. SnO_2) when required to increase surface area.

In this way, the iridium loading can be reduced 1-2 orders of magnitude, as demonstrated on lab-scale, while using methods that are compatible with currently used manufacturing methods and materials. The same methods can be used to apply anti-corrosion, protective and other supporting films on e.g. the PTL or BPP. TRL level is currently 4-5.

The next steps include scaling up and validation of the S-ALD equipment to/on mass production scale. To realise this, the requirements for mass production need to become clear, and some level of standardisation (e.g. in terms of size, shape and materials, but also test protocols) will be beneficial to reduce costs and lead times. Also, access to facilities for qualification and validation will be essential.

Source: Paul Poodt – SparkNano

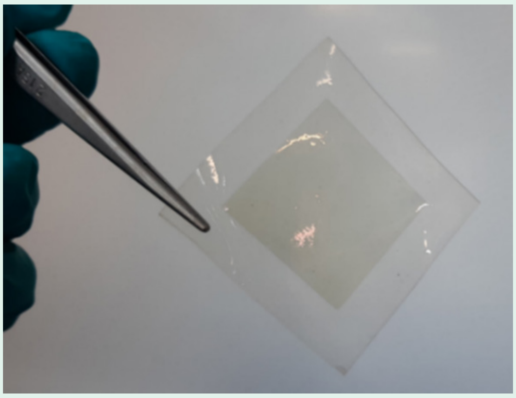

Figure 9. IrO_2 (grey square) deposited on a 5 x 5 cm^2 Nafion 115 test substrate by Spatial ALD.

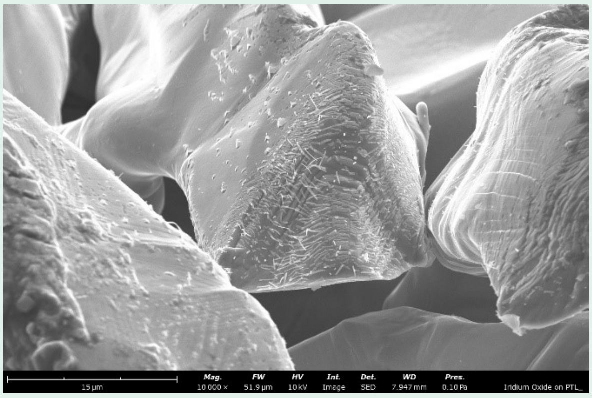

Figure 10. 3D structure of IrO_2 coated on a PTL using spatial-ALD.

Box 6. Gas-phase coating of catalysts to improve electrolyser efficiency and performance

Delft IMP provides ultrathin coatings, which can eventually enhance the stability of the catalysts and increase the efficiency of utilisation of scarce metals such as platinum and iridium.

This is achieved by depositing small clusters of highly dispersed iridium or ultra-thin films on the surface of the substrate by using Delft IMP gas-phase coating. This can have a strong impact on the performance of the electrolysers, in the price of the catalysts, since less expensive metal is used, and its lifetime, since the catalysts will be more stable.

The Delft IMP technology is not limited to creating Platinum Group Metal (PtGM) catalysts and we will therefore also cooperate with knowledge partners to enhance and scale up possible new developments of non-PtGM catalysts. The technology is currently being tested on a small scale to demonstrate a proof the concept and proof of scalability of the materials and coating technology.

Source: René Hauser – Delft IMP

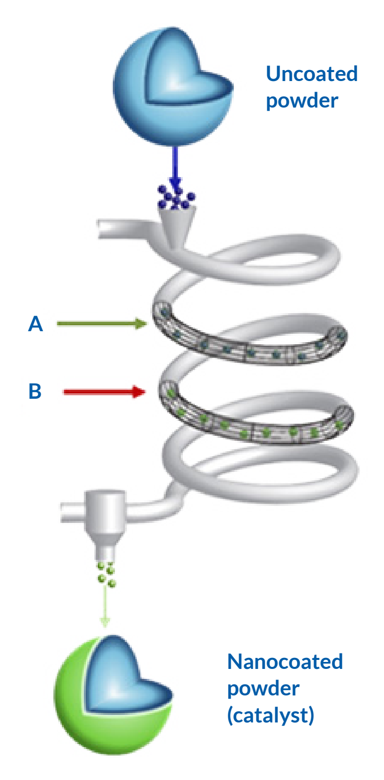

Figure 11. Schematic of Delft IMP's gas phase coating process used to deposit ultra-thin films on the surface of a substrate powder to make catalyst particles.

Box 7: Spatial ALD on- and of new and advanced 3D support and catalyst materials

In combination with other materials and methods, the ultra-thin-film technology Spatial ALD can design and make advanced support- and catalyst layers on optimised 3D structures, to minimise PGM use while at the same time maximising performance and stability.

New catalyst materials and structures (PGM and beyond PGM) enabled by ALD are being developed, as well as novel concepts, like nano-caging of catalyst particles, to improve stability. Currently the Eindhoven based SALD b.v. is involved in the Dutch alkaline electrolyser project “HyScaling” to enhance the HER performance of an electrolyser by depositing ultra-thin ruthenium layers on structured nickel electrodes. These promising novel concepts still require extensive R&D effort, often on a fundamental level, to explore their potential. Therefore, close collaboration of industry with universities and R&D institutes is the key to move forward and should be enhanced.

Source: Peter Visser - SALD

Figure 12. A spatial ALD tool equipped with glove box to deposit high quality SnO_2 films.

Figure 13. Ruthenium deposited on an aluminium oxide coated wafer.

Third Generation: Integrated Design and Manufacturing

The third-generation PEM technology originates from the need to improve electrolyser systems to better suit the needs of the future renewable energy system, through flexible and efficient operation. This requires radical innovations that alter the system architecture. Instead of improving the performance of separate components, the focus is on integrating all components and optimising performance of the system as a whole.

In this generation, there are plenty of opportunities for the high-tech manufacturing industry. For example, instead of putting the catalyst on the membrane, it could be deposited on a dedicated PTL structure instead. See “Box 8” on page 29 for an example. The deposition process can be tuned to maximise the amount of active catalyst. Additionally, the PTL could be integrated with the BPP and solution-coated membrane precursors. Alternatively, all three materials could potentially be combined into one material. All these concepts require different combinations of manufacturing techniques. An important potential venue of research and development is the encapsulation/anchoring of expensive catalysts, such as iridium, on the atomic scale within matrix structures to prevent them from leaching out under long-term electrolyser operation. This could potentially significantly prolong the accumulated current density (in for example MAh/cm^2) that a single catalytic site can function.

All these innovations are currently at a low TRL. Most developments still occur at the laboratory scale and are fragmented across different supply chains and research institutions. Alignment between the high-tech manufacturing industry and the electrochemical research community is essential to accelerate deployment of third-generation PEM technology.

Box 8: Application of an ultrathin layer of iridium on a titanium PTL, instead of on a membrane

Recently, TNO – in a collaborative effort between researchers from the Faraday laboratory in Petten and TNO at Holst Centre in Eindhoven - demonstrated reduction of 200x iridium while keeping on average 30% of performance conversion.[11]

It is expected that with further optimization we can reach the current state-of the art performance with respect to efficiency. Researchers applied an ultrathin layer of iridium as a catalyst material on a porous transport layer of titanium, instead of on a membrane, as is presently customary. The functioning and stability of the new method has been proven after different lab tests. Little to no degradation occurred after initial stress testing. On top of this, the membrane remains iridium-free, making it easier to recycle and reuse. It should be possible to apply the technology at a large scale in 2030.

Source: TNO[12]

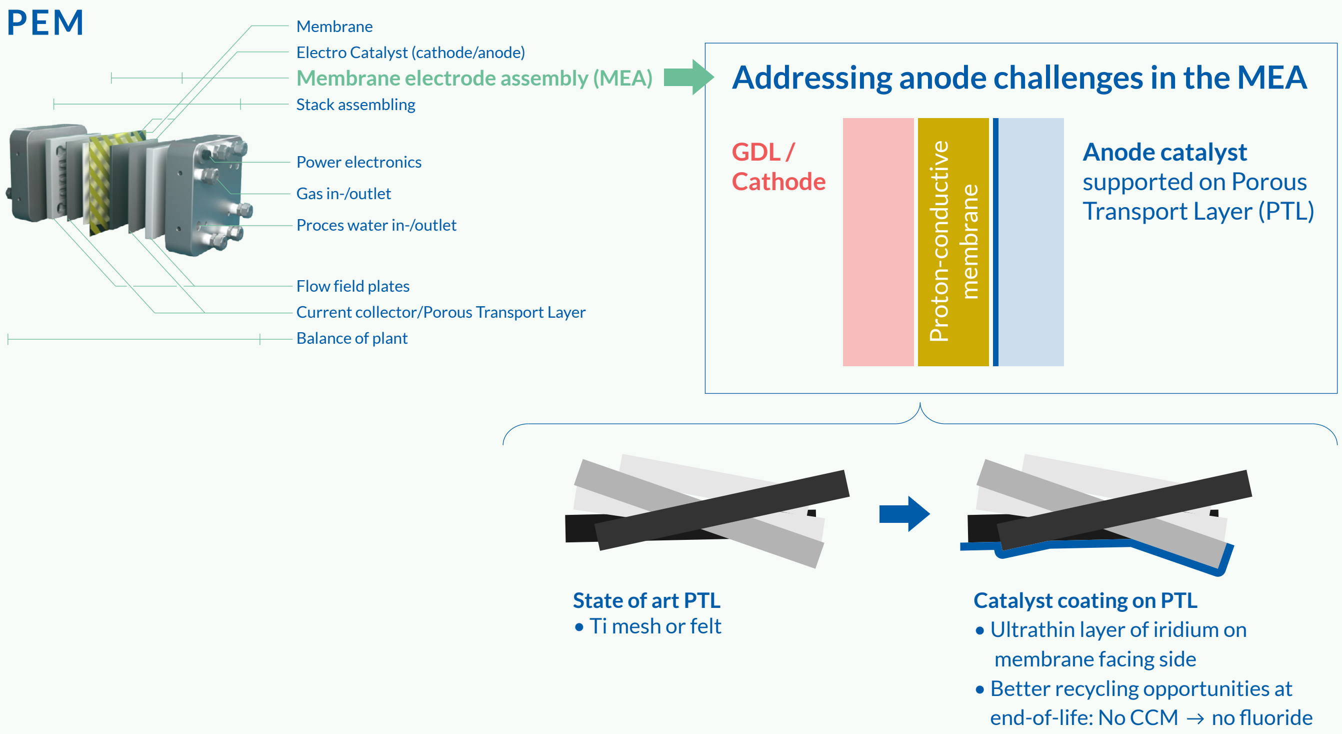

Figure 14. Solutions for advanced MES designs. Source: TNO.

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[11] TNO, „Breakthrough electrolyser development: 200 times less iridium needed," TNO, 24 10 2022. [Online]. Available: https://www.tno.nl/en/newsroom/2022/10/breakthrough-electrolyser-development. [Geopend 21 12 2022].

[12] Idem.

4. CONCLUSIONS AND RECOMMENDATIONS

To meet the energy transition challenge, manufacturing capacity of electrolysers has to scale up while simultaneously improving the design of the technology on a fundamental level, from its basic materials, to components, to entire system architecture.

This paper projects a plausible future where improvement and scale-up of electrolysis technology may very well go hand in hand. This is the promise that the high-tech manufacturing sector brings. At the same time the arguments and showcases presented are by no means a given. They merely represent opportunities that, in order to become manifest, need to be acted on. This will require substantial effort from a variety of stakeholders ranging from different disciplines and sectors.

Further development and upscaling of high-tech solutions requires an intimate bridging of the worlds of (process) industry, electrochemistry and high-tech manufacturing. Moreover, given the nature of the electrolyser manufacturing value chain, where equipment suppliers are highly dependent on a small number of OEMs, who are themselves dependent on government policies and as yet poorly articulated markets, a concerted effort is needed to push for radical innovations on behalf of the high-tech manufacturing sector. This is crucial in the face of the challenges of material scarcity and energy efficiency. The following recommendations serve as main guidelines for concerted strategic action.

Policy & Market Constraints

Key Challenge: Given EU wide ambitions to ramp up electrolysis capacity, the full potential of the European technology ecosystem needs to be utilised for implementing first generation electrolysers while simultaneously accelerating the development and utilisation of the second- and third-generation electrolysers developed to be more efficient and to have an inherently circular design.

Actions: The EU and its member states should – in addition to current targets for green hydrogen production capacity – **set progressive market targets to specifically stimulate development of second-generation and third-generation production capacity**; for instance: 100MW in 2028 – 500MW in 2030 but this should be discussed. These targets should be backed up by policy incentives and embedded in a European technology leadership strategy. **This is to avoid an early lock-in into first-generation electrolysis technologies and to improve chances to meet the required growth ambitions beyond 2030**. This action is in line with recently announced goals of the European Union to set EU-targets on industrial production capacity for crucial renewable energy technologies in order to improve strategic autonomy.[13]

Roles:

- Governments, businesses and research organisations should agree (and set targets) on performance criteria involving scarce materials use, sustainability (e.g. use of fluor-based membranes), and recyclability. The idea is to set a standard for high value electrolyser systems in terms of various dimensions (also safety, circularity, performance, sustainability).

- Governments and public actors should backup policy targets with a clear industry vision and policies that help create a market for electrolysers that perform better on sustainability criteria such as materials efficiency, energy efficiency, toxicity.

- Research and Technology Organisations can, together with industry partners from all involved sectors, provide reliable insights in the state-of-the-art of available technologies, and based on this, propose milestones for an ambitious yet feasible roadmap.

Industry & Supply Chain

Key Challenge: Accelerated implementation of second- and third-generation technologies will require the alignment of numerous industry players across the electrolyser manufacturing supply chain. Given the currently still limited and poorly articulated market demand, even with policy targets in place, the knowledge exchange, cooperation and integration of (potential) value chain partners from different sectors occurs only haphazardly. The risk is that this will hamper the timely development of advanced production technologies and hence negatively impact the speed and direction of the energy transition.

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[13] At the moment Europe has a strong position on PEM technology, whereas China leads the Alkaline technology. Source: A. Klevstrand, „www.hydrogeninsight.com," 17 November 2022. [Online]. Available: https://www.hydrogeninsight.com/electrolysers/chinese-companies-take-top-three-slots-in-bnefs-list-of-worlds-20-largest-hydrogen-electrolyser-makers/2-1-1355610. [Geopend 13 February 2023].

Actions: For the electrolyser manufacturing industry to gain momentum, it is critical to not merely act as suppliers to the first commercial projects, but to work together towards shared industry milestones. This involves ongoing engagement from governments, research organisations and industries across the value chain which is to some extend already happening in many platforms, networks and projects. Yet, this process can and should be accelerated by **developing a EU wide next-generation electrolyser program that is dedicated to the accelerated development, implementation and scale up of second- and third-generation EU manufactured technologies**. The program should provide a stimulus for actually working together of manufacturing partners. First on research and engineering, and then especially on implementation in close collaboration with OEMs and process industry. **The program should facilitate an infrastructure for testing and validation on the level of 1-5 MW-systems**.

Roles:

- Governments and public actors should financially support the next-generation electrolyser program, especially where infrastructure is concerned. Moreover, governments should incentivise potential launching customers from industry to take part in the experimentation activities.

- OEMs should take a leading position and work with urgency and serious capacity on scaling-up the second- and third-generation solutions as discussed in this paper. It is in their best interest to get a head start in addressing the critical challenges of electrolyser manufacturing with respect to materials scarcity and efficiency.

- Component suppliers of OEMs would be wise to develop conceptually novel materials with improved performance to position them ahead of the competition.

- Industrial end users should work together with innovative electrolyser OEMs to allow advancement and implementation of more efficient technologies and thereby become more competitive.

- For OEMs and component suppliers it is critical to take scalability of process innovation into account, even for R&D activities in an early stage.

- Research and Technology Organisations can provide support as technological experimentation should be complemented by innovation orchestration and business development activities. For example, it is key to facilitate structural cross-sectoral exchange of knowledge and experience and building of trust. Industry and Research and Technology Organisations should work towards (industry and product) standards to enable modularity, alignment and integration. This includes benchmarking criteria for performance indicators.

Research & Innovation

Key Challenge: The EU and its member states are well positioned as a technology leader in the field of hydrogen and fuel cells technology. Still the field, with its expertise, facilities and networks is rather fragmented and unaligned. The risk is that insights and lessons learnt from innovation and experimentation within the context of specific projects or within certain member states does not add up and contribute to a common ambition. The challenge is to accelerate learning and innovation by better leveraging the knowledge position and technology infrastructure of the entire European research ecosystem. This could position the EU electrolyser manufacturing industry to be a global frontrunner.

Actions: It is critical to work towards a shared EU R&D infrastructure for testing and validation by aligning and connecting facilities. The benefit is that European industries gain access to a broad basis of support for testing, validation and benchmarking. Also, large investments in key demonstrator facilities, for higher TRL, become more viable. **For all upcoming publicly funded pilots and demonstration projects, data sharing and monitoring of system performance should be a prerequisite to accelerate learning**. For more in-depth recommendations on how to accelerate knowledge exchange across the EU, see the EU HyspeedInnovation agenda.[14]

Roles:

- Research and Technology Organisations can provide expertise for independent testing and validation of first-, second- and third-generation technologies, from single cell up to industry MW scale.

- Research and Technology Organisations should take the lead in developing a shared infrastructure for testing and validation. A solid starting point is to develop

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[14] CEA, Fraunhofer, Hydrogen Europe, Jülich, Sintef, TNO, „*HySpeedInnovation: A joint action plan for innovation and upscaling in the field of water electrolysis technology*," 2020.

a shared database concerning project references, equipment, testing protocols, etc. They should maximise impact of national labs by sharing references on the performance of electrolyser components and stacks, and to organise Round Robin testing to harmonize methodologies.

- Governments, EU and member states should make sharing of data and learnings of the subsidised research, demonstration and pilot projects mandatory.
- The JRC could act as an independent actor for the creation and coordination of a data safe house with Open Access policy for sharing aggregated data and learnings.
- Research and Technology Organisations can provide a data structure and methodology for aggregating, processing and systematically analysing the anonymized aggregated data. This has successfully been done in the US through the DoE hydrogen program.
- Research and Technology Organisations can, together with ecosystem partners, shape consortia, for instance by organising collaborative research and development initiatives. The set-up of such programs can be aimed at developing next-generation electrolyser technology on a pre-competitive basis. Industry partners that participate can share the individual technology risk and gain collectively by reducing the time-to-market and increasing the potential for market uptake of novel technologies.[15]

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[15] TNO, „*TNO and partners to work together to boost the efficiency of renewable hydrogen production*," TNO, 26 4 2022. [Online]. Available: https://www.tno.nl/en/newsroom/2022/04/tno-partners-work-together-boost. [Geopend 23 2 2023].

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CONTACT

This discussion paper is meant as a starting point for dialogue across disciplines. At TNO, as well as within the VoltaChem and TNO at Holst Centre shared innovation programs, we believe that it is the alignment of disciplines and expertise areas that will provide opportunities for timely development of advanced electrolysis technology.

For more information on TNO's activities, please contact:

Lennart van der Burg
Business Development Power-2-Hydrogen
VoltaChem
lennart.vanderburg@tno.nl

Roald A. A. Suurs
Senior Scientist Integrator
TNO Elektrolyser Makersplatform NL
roald.suurs@tno.nl

Emilio Manrique Ambriz
Business Development Manager
TNO at Holst Centre
emilio.manriqueambriz@tno.nl

TNO has a broad portfolio of expertise and experience with hydrogen-related efforts that span a wide range of area's: from policy and market analysis to technological developments across the entire value chain of hydrogen. Within **Joint Innovation Centres** (JICs) TNO collaborates with relevant ecosystem partners to accelerate market uptake of new developments. Within **VoltaChem**, a business-driven Shared Innovation Programme powered by TNO, development and implementation of new electrochemical technologies is accelerated. At **TNO in Holst Centre**, new high-tech electrolysis components based on scalable manufacturing technologies are developed for next-generation electrolysers. Within the **Elektrolyser Makersplatform NL**, support is provided by TNO's innovation orchestrators for Dutch (SME) supply chain actors with the ambition to produce (components of) electrolysers.

ENDORSEMENTS

At TNO we believe that it is the alignment of productive efforts, in research, development and upscaling, throughout the manufacturing supply chain that will provide the real and lasting opportunities needed to upscale improved electrolysis technologies. The partners listed below endorse this message and are already part of a cooperative effort to move from vision to reality.

delftIMP
INTENSIFIED MATERIALS PRODUCTION

Delft IMP is a spin-off from Delft University developing a technology to produce more efficient materials to contribute to the energy transition. Hydrogen production with electrolysers is one of these fields where Delft IMP wants to contribute by producing more stable catalysts, using scarce resources, such as platinum and iridium, more efficiently. This vision of Delft IMP is a perfect match with the target of The Netherlands to create a hydrogen network by 2030, in which achieving a resilient production technology for the catalysts will be crucial. www.delft-imp.nl

SALD
SPATIAL ALD
INNOVATORS

SALD B.V., based in Eindhoven, has extensive industrial experience in atomic-scale nano-coatings. Its Spatial Atomic Layer Deposition process is key to the required upscaling of nanolayer material depositions for electrolysers. For developing new thin-film materials for next-generation electrolysers, SALD developed a very flexible and versatile lab tool. This Spatial ALD process, with special 3D-printed deposition heads, is scalable to high-volume equipment. www.spatialALD.com

SPARKNANO

SparkNano B.V. is an OEM equipment company, supplying Spatial Atomic Layer Deposition lab- and mass production equipment for applications in the sustainable energy domain, including electrolysis, fuel cells and energy storage. For PEM electrolysis, SparkNano offers solutions to apply high-coverage and low-loading-thin-film catalyst layers like IrO_2 and Pt on 3D and complex substrates with atomic-scale control of the amount of material deposited. Furthermore, supporting- and protective films for catalyst- and other components of the PEM stack can be applied with SparkNano's products. SparkNano has a strong focus on scaling-up Spatial ALD equipment and processes from lab-scale to mass production, aiming at high throughput and low costs while ensuring high utilisation efficiencies of scarce materials. www.spark-nano.com

veco

VECO B.V., part of the Muon group, is a world-leading manufacturer of micro-precision parts. It serves the world's most innovative, high-tech companies that demand high quality and precision. Veco's core competences are know-how in Photolithography and Electroforming, in-house process engineering and R&D, extensive application know-how, high volume production abilities at very high precision in reproducible processes, extensive clean room facilities (> 2000 m^2) and fully automated inspection equipment is available. As electroforming is an additive manufacturing process, there is zero waste of materials and electroforming also gives a great freedom of design. This means that nearly any surface texture can be made to achieve large surface areas and high open area. To enhance surface properties Veco is also equipped with coating processes. www.vecoprecision.com

vsparticle

VSPARTICLE is an equipment OEM supplying nanoparticle synthesis and deposition equipment based on a completely liquid-free (dry) process. VSPARTICLE's tools enable manufacturing of catalyst layers with a very large active area enabling high performance combined with very low precious metal content. VSPARTICLE's equipment converts bulk materials into a deposited catalyst layer in a single step, which significantly reduces the costs of these catalyst layers. Besides developing mass production equipment, VSPARTICLE provides R&D equipment suitable for a broad range of applications (including electrocatalysis). www.vsparticle.com

Appendix I: Components Functionality, Design Trade-Offs, Potential High-Tech Solutions

	Membrane	Catalyst	PTL	BPP
Function of component in the stack	• Conduct protons from anode to cathode. • Separation of product gases. • Electrical insulation of electrodes.	• Catalyse the oxygen and hydrogen evolution reaction.	• Conduct gas & liquid between BPP and membrane. • Remove heat from catalyst to liquid flowing through channels. • Conduct current.	• Collect current and guide the flow of water and gases in and out of the PTL. • Provide mechanical stability to stack of cells.
Issues	• Environmental issues of fluor (PFSA regulation). • Suffers from degradation by metal ions.	• Adherence of catalyst to the membrane. • Making it thinner without cracking. • Iridium is a scarce material. • Oxygen bubbles on the anode.	• Oxygen bubbles on surface. • Surface passivation leading to increased overpotentials (poor electrical conductivity)	• High costs. • Corrosion and surface passivation, lead to lower conductivity. • Corrosion products affect membrane • Gold and platinum are scarce and expensive.
Trade-offs	• Thickness: ohmic resistance, gas tightness, tolerance to differential pressure. A thinner membrane with a rough PTL could also cause short circuit. • Reinforcement: mechanical strength, ohmic resistance.	• Transport properties: lateral & in-plane conductivity. • Material usage: catalyst needs to work efficiently, with as little material use as possible. • However, thin layers are less stable.	• Thickness: mechanical strength (to support the MEA) increases with thickness, while lateral conductivity decreases and mass transport resistance increases. • Catalyst material choice: performance vs. adhesion.	• Material choice: cost and type of manufacturing vs. corrosion stability.
Potential solutions	• Multilayer membrane systems, where each layer has a designated property. • Hybrid membrane material, where multiple materials are mixed together. • Optimisation of the reinforcement structure to improve through-plane conductivity and cross-plane strength. • Recombination catalyst in a thinner membrane, that prevents H2 crossover.	• Intermediate layer between catalyst & membrane to improve adhesion. • Possibility of patterned layers, to improve counter current transport of liquid and gas. • 3D structured patterns to maximise surface area. • Mesh to improve conductivity in gas diffusion electrodes.	• Hybrid solution: using a non-conductive material as reinforcement with a conductive coating. • Gradation of pore size from small to large, from the catalyst surface towards the BPP. • PTE: coating the PTL instead of the membrane or coating both.	• Alternative coatings: Ti, TiN, Ta, Ta2O5, Nb. • Can be coated to reduce contact resistance and avoid corrosion of BPP.
Interesting high tech manufacturing technologies	• Slot die coating. • Lamination. • In-situ membrane manufacturing with curing and pre-formulating combined materials.	• Inkjet type printing. • Dry nanoparticle synthesis and deposition based on spark ablation. • Spatial atomic layer deposition (s-ALD). • Plasma-enhanced chemical vapor deposition (PE-CVD). • Multi-layered catalyst-membrane structure with in-situ membrane realisation and thin film catalyst layers.	• Spatial ALD. • Dry nanoparticle synthesis and deposition based on spark ablation. • Combinatory approaches (PVD, CVD etc.) with lithography. • Photosensitive materials and lithographic patterning of metal and support layer(s) - organic and inorganic.	• Other production techniques could be used to apply coatings of less scarce materials: • Electroplating. • Physical vapor deposition (PVD). • Chemical vapor deposition (CVD). • Atomic layer deposition (ALD).

VoltaChem

VoltaChem is a Shared Innovation Program, initiated by TNO (the Netherlands Organisation for Applied Scientific Research). VoltaChem connects experts from the renewable energy, equipment supply and chemical industry to accelerate the development, integration and implementation of disruptive Power-2-X technologies in fuels, materials and food applications. In close cooperation with partners from the process industry, the energy sector and equipment supply & licensors we work on innovations for both new and existing processes that are essential to meet the goals of the Paris Agreement.

www.voltachem.com

Holst Centre

With the establishment of Holst Centre in 2006 by imec and TNO, expertise in wireless sensor technologies and flexible electronics was brought under one roof at the High Tech Campus Eindhoven.
The sharing of specific knowledge in an open structure, makes it possible to align research and innovation with societal issues in the fields of health & vitality, energy & climate and mobility & industry 5.0. To help solve those societal challenges, Holst Centre connects the Brainport region with a global ecosystem of industrial and academic partners.
Using the expertise, knowledge and technologies of TNO and imec, technological innovations are developed so that the partner companies can take them to the market.

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TNO innovation for life